Developing a framework for integrating life cycle environmental and economic assessment of buildings

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Declaration

This is to certify that:

i) the thesis comprises only my original work towards the PhD,

ii) due acknowledgement has been made in the text to all other material used,

iii) the thesis is fewer than 100 000 words in length, exclusive of tables, maps, bibliographies and appendices.

Signed:

Monique Schmidt

Date: 26/04/2018

Abstract

There is growing concern about the effect that buildings are having on the environment. Mitigation strategies tend to focus on one life cycle stage, usually the operational stage, leaving the other life cycle stages, such as manufacturing and construction, largely ignored. The slow uptake of whole life cycle design is further hindered by the uncertainties associated with the economic implications of life cycle environmental optimisation. Evaluating building design options with a focus on simultaneously optimising life cycle environmental and economic performance is difficult due to a lack of comprehensive and accessible tools. Integrating life cycle perspective tools such as life cycle assessment (LCA) and life cycle costing (LCC) can help address this uncertainty and demonstrate the trade-offs between economic and environmental considerations, ultimately aiding the decision-making process. This study describes the development of a comprehensive environmental and economic framework for integrated building evaluation and demonstrates its potential by applying it to built environment examples. This demonstration highlights the fact that solutions for improving the environmental performance of buildings are not always the most expensive, as previously thought, especially when assessing the building's performance from a life cycle perspective. It also shows that building design strategies that aim to decrease environmental impact can also have a beneficial effect on the economic performance of buildings. This study further demonstrates the large uncertainty associated with life cycle studies and highlights the various sensitivity parameters, such as period of analysis and discount rate, which must be taken into account when considering the life cycle results. The framework will allow building designers to investigate different design options and base their final selection on options that maximise environmental performance, while providing an understanding of the economic implications of this optimisation. This should lead to the adoption of building strategies that consider the whole building life cycle and improve the environmental performance of the built environment.

Publications resulting from work reported in this thesis

Journal papers

- Schmidt, M and Crawford, R.H, 2018 A framework for the integrated assessment of life cycle greenhouse gas emissions and life cycle cost of buildings. Energy and Buildings.

Conference papers

- Fouché*, M. & Crawford, R. H, 2015. The Australian construction industry's approach to embodied carbon assessment: a scoping study. *In:* CRAWFORD, R. H. & STEPHAN, A. (eds.) *Living and Learning: Research for a Better Built Environment: 49th International Conference of the Architectural Science Association 2015.* Melbourne, Australia: The Architectural Science Association and The University of Melbourne.
- Fouché*, M. & Crawford, R. H, 2017. Towards an integrated approach for evaluating both the life cycle environmental and financial performance of a building: A review. *International High- Performance Built Environment Conference – A Sustainable Built Environment Conference 2016 Series (SBE16), iHBE 2016.* Sydney: Procedia Engineering.
- Schmidt, M & Crawford, R.H, 2017 Developing an integrated framework for assessing life cycle greenhouse gas emissions and life cycle cost in buildings. *Creative Construction Conference 2017 (CCC), Croatia*, Procedia Engineering

Book chapter

- Crawford, R. H., Stephan, A. & Fouché, M, 2018 Embodied carbon in buildings. Cambridge Springer.

General press

- Fouché*, M., Crawford, R. H., Teh, S. H., Rowley, H. & Wiedmann, T. 2015, Integrated Carbon Metrics (ICM), RP2007: Scoping Study Results NSW, Australia: CRC.

** Name change from Fouché to Schmidt December 2015*

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List of acronyms

AHP	Analytic hierarchy process
BC	Base case
DCF	Discounted cash flow
DR	Discount rate
EC	Embodied energy coefficient
EE	Embodied energy
EF	Emission factor
EGHGE	Embodied greenhouse gas emissions
EPD	Environmental product declaration
GBDS	Green Building Design Studio
GFA	Gross floor area
GHGE	Greenhouse gas emissions
IEE	Initial embodied energy
IES	Integrated Environmental Solutions
IO	Input-output
IOH	Input-output-based hybrid analysis
IR	Inflation rate
IRR	Internal rate of return
ISO	International Standards Organisation
LCA	Life cycle assessment
LCC	Life cycle cost
LCCf	Life cycle carbon footprint
LCE	Life cycle energy
LCEA	Life cycle energy analysis
LCGHGE	Life cycle greenhouse gas emissions
LCI	Life cycle inventory

MAC	Marginal abatement cost
Max	Maximum
Min	Minimum
MCDM	Multi criteria decision-making
MSL	Material service life
NPC	Net present cost
NPV	Net present value
OAT	One-at-a-time approach
OGHGE	Operational greenhouse gas emissions
PDS	Passive design strategies
POA	Period of analysis
REE	Recurrent embodied energy
TER	Total energy requirement
TERBS	Total energy requirement of the building sector
LCIA	Life cycle impact assessment

1.

Introduction

1.1. Problem Statement

There is growing concern about the poor environmental performance of buildings. It has been reported that buildings account for 39% of energy related global greenhouse gas emissions (GHGE) (when considering residential, commercial and construction related emissions),which have more than doubled since 1970 (UN Environment & International Energy Agency (2017)). In Australia, one of the world's largest emitters of GHGE per capita (Climate Council, 2015), the building sector accounts for almost one quarter of the country's GHGE (ASBEC, 2016). GHGE are a significant contributor to climate change and have most probably been the dominant cause of the observed global warming since the mid-20th Century (IPCC, 2014). It is therefore crucial that an effort is made to mitigate building related GHGE, particularly with regard to the fact that an estimated 5.4 million additional dwellings are expected to be built in Australia over the next 30 years (Property Council of Australia, 2015).

Fortunately, buildings represent one of the largest and most attractive opportunities to reduce GHGE (Climate Council, 2015). For example, if Australia's building sector reaches zero carbon emissions for the operation of residential and commercial buildings by 2050, it will contribute some 28% to the country's 2030 emission reduction target, in accordance with the Paris Climate Change Agreement, and save up to AU$20 billion (ASBEC, 2016). To this end, government and industry have mostly focussed on decreasing building related operational GHGE (the GHGE associated with energy needed for heating, cooling, lighting etc.) through strategies broadly classified as either passive (strategies that deal passively with the building envelope, form and site), active (such as strategies that deal with the building services) or energy generation (such as solar power) (Davis Langdon, 2013). The emphasis is firstly on using passive design strategies (PDS) to decrease a building's energy demand and related GHGE, followed by active and generation strategies (Davis Langdon, 2013; Rodriguez-Ubinas et al., 2014; Lu et al., 2015). However, often these operational related strategies are resource and energy intensive to manufacture and implement within a building (De Wolf et al., 2015). For example, some buildings with a high level of insulation, one of the most popular PDS (Williams, 2012), result in lower operational GHGE, but at the expense of higher embodied GHGE, often offsetting any savings (Stephan et al., 2013). These embodied GHGE, resulting from the manufacture, transportation of materials and products and the construction process, have been estimated to equate to between 10% and 97% of the total life cycle emissions of a building (depending on building location, function, material use and assumptions about service life and energy supply) (Chastas and

Theodosiou, 2016). It is thus critical that buildings are designed from a whole life cycle perspective, using an approach that considers both embodied and operational GHGE. Emission reduction strategies can then be assessed to ensure they provide net emissions savings over the long term. Life cycle assessment (LCA) is a tool that enables the use of this life cycle perspective and can be used to inform decision-making aimed at reducing a building's energy demand and GHGE.

Notwithstanding significant developments in the field of LCA, the uptake has been slow. Some of the key barriers affecting the uptake of LCA within industry, especially with regards to the consideration of embodied GHGE, were highlighted in a report published by UKGBC (2014) that placed consistency of method at the top of the list, followed by the availability of comparable data and the provisions of mandatory legislation. These barriers have been well documented in the literature (for example Menzies et al. (2007), Dixit et al. (2012a); Farhan et al. (2014); and Ariyarante and Moncaster (2014)). However, one such barrier that has not yet been widely explored yet, as identified by the aforesaid UKGBC report, as well as a recent survey completed for the CRC for Low Carbon Living (Fouche et al., 2015) (and provided in more detail in Fouche and Crawford (2015)) is the uncertainty attached to the economic implications of life cycle GHGE reduction strategies. Project developers and building owners have limited knowledge of the economic implications of including building strategies that consider both the embodied and operational GHGE of a building, and design teams do not have enough information or the appropriate tools to address these concerns. The limited number of studies on this subject that are available state that budget constraints, the limited demonstration of cost benefit and difficulties in estimating the market value of embodied emissions hinders the implementation of life cycle optimised building strategies (Langston and Langston, 2008; Ariyarante and Moncaster, 2014; Wu et al., 2015). There has also been a tendency to focus only on the capital cost or the operational cost, excluding other life cycle stages such as replacement cost (Jackson, 2008).

Several methods for quantifying the life cycle economic performance of a building are available, such as life cycle costing (LCC). However, even though both LCC and LCA are based upon the same life cycle perspective, they are often used in isolation. This has a negative impact on the consideration of important relationships and trade-offs between economic and environmental performance when comparing and evaluating potential design strategies for a building (Bierer et al., 2015). There is an increasing number of studies that include both LCA and LCC analyses, for example Mithraratne and Vale (2004), Ristimäki et al. (2013); and Schwartz et al. (2016). However, these studies have significant limitations, as demonstrated in Fouche and Crawford (2017). They tend to focus on exemplar buildings (buildings that are already classified as energy efficient) and not traditional buildings (which make up most of the built fabric); have a lack of transparency around the manner in which the LCA and LCC are performed and furthermore rely on methods of LCA that are known to be incomplete. There has also been an increase in the availability of LCA and LCC tools, but they are plagued by various issues such as inconsistent methodologies, incomplete system boundaries, their time intensive nature and need for expert knowledge. These tools also perform their analyses quite separately, making it difficult for the user to find the ideal design solution based on optimised environmental and economic performance. There is a need to integrate LCA and LCC, so that both the environmental and economic value of potential emissions reduction strategies for buildings can be included in the decision making process, especially at an early design stage, when there is are greater prospects of influence on the design. A framework provides an ideal platform for this integration as it can provide a basic structure and system of rules and ideas available to assist in the decision-making process (Merriam-Webster, 2017; Cambridge Dictionary, 2017) and has been explored in a limited number of studies such as Deng et al. (2008) and Heijungs et al. (2013).

1.2. Research Aim

The aim of this research is to develop a framework for the integrated optimisation of the environmental and economic performance of buildings.

1.3. Scope

Environmental optimisation of buildings includes several categories such as GHGE, energy and water, for example. The Australian building sector represents one of the key areas for the mitigation of GHGE (World Resources Institute, 2013), which is the rationale behind its selection for the focus of this study. This study uses of the global warming potential (GWP) impact category, which is the contribution of a substance to the greenhouse effect (LCANZ, 2013) and therefore one of the main contributors to climate change (IPCC, 2014). GHGE can be translated into GWP, which include gases such as carbon dioxide and methane. The life cycle stages included in the GHGE analysis are initial embodied GHGE, recurrent embodied GHGE and operational GHGE. Other life cycle stages such as demolition have not been included in this research due to the limited amount of data available on this life cycle stage (Moncaster and Song, 2012) and its probable insignificance (Crawford et al., 2010). The life cycle cost stages included in this study are capital cost, operational cost and replacement cost. In order to develop an integrated environmental and economic framework, different building strategies were used to examine the relationship and trade-offs between environmental and economic factors during the course of their optimisation. So as to limit the scope of this study, only passive design strategies have been included due to their prominence on the energy hierarchy and applicability to the building sector (McGee, 2013). The scope of the study is illustrated in Figure 1.1.

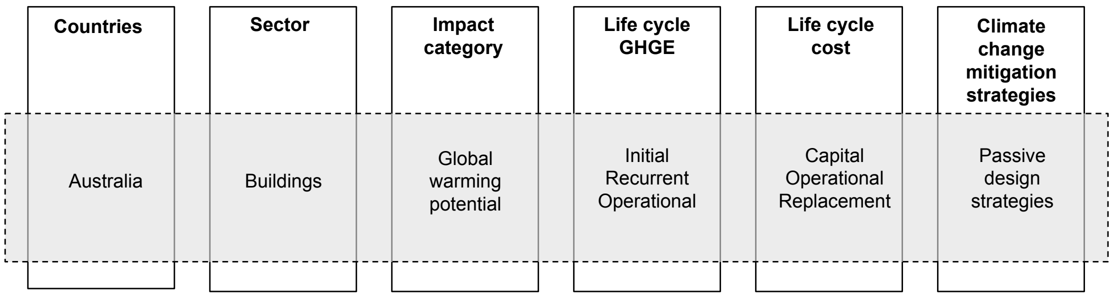


Figure 1.1 Scope of study

1.4. Thesis structure

The structure of this thesis is set out hereunder.

Chapter 1, *Introduction*, provides a brief overview of the problem, the aim and scope of this study and the structure of this thesis.

Chapter 2, *Literature Review*, describes the context of the study and key aspects, which are to be considered within the study. This chapter includes an overview of energy and GHGE assessment methods for buildings, including both the embodied and operational assessment methods. A detailed explanation of LCA is provided, including the types, standards, framework, tools, sensitivity analysis and limitations. The LCA section concludes with a brief overview of its application to energy and GHGE assessments. Thereafter, an overview of LCC is provided along with its key terms and concepts. This is then elaborated upon with an explanation of the discounted cash flow analysis techniques used within LCC, and other aspects to be mindful of, such as risk, forecasting, sensitivity analysis and relevant barriers. The last section of this chapter describes the current state of knowledge regarding the integration of LCA and LCC. This chapter concludes by highlighting the current limitations plaguing their successful integration, leading into this study's research questions.

Chapter 3, *Research Design*, translates the research aim and questions into practical research steps. Various decision-support techniques available to aid this study's framework development are discussed and selected, for example LCA, LCC and Multi-Criteria Decision Making. This is followed by a detailed overview of the appropriate environmental and economic quantification techniques that must be included in the framework. This chapter concludes with an overview of the methods available to integrate results, visual output options and selected sensitivity analysis method.

Chapter 4, *Developing a framework an integrating life cycle environmental and life cycle economic assessment of buildings*, builds upon the research designs theoretical framework in order to develop this study's integrated framework. This includes listing of the steps required in this development process, the framework approach and required framework input parameters. This chapter concludes by validating the environmental and economic quantification techniques selected in the previous chapter by applying it to a case study building.

***Chapter 5**, Demonstration of the framework*, applies the framework developed in the previous chapter to a case study building in order to provide an example of how it can be used and the type of results that can be achieved by an integrated assessment. Additional aspects are incorporated in this chapter in order to demonstrate the framework's flexibility including two different locations and two different building passive design strategies. A detailed sensitivity analysis (and comparison to other similar studies) is included for each form of assessment for purposes of testing the reliability and robustness of the framework results.

Chapter 6, *Discussion*, provides a critical analysis of the findings of this study in the context of previous research. This includes an overview of the relationship and trade-offs between LCA and LCC, the uncertainty of life cycle studies and the limitations of this research and potential improvements to the integrated framework.

Chapter 7*, Conclusion*, provides a concluding summary of the thesis findings along with identifying any limitations to be aware of and any future areas of research that can be elaborated on in future studies.

2.

Literature Review

2.1. Introduction

This chapter provides context to buildings and their energy and greenhouse gas emissions (GHGE) performance from a life cycle perspective. The current barriers and limitations of this life cycle perspective are discussed, such as uncertainties in respect of financial cost and the critical need to integrate environmental and economic performance. This is followed by an overview of the quantification methods available to assess the life cycle environmental performance and economic cost in buildings. The current state of integrated environmental and economic analysis is discussed followed by the methods available to aid this integration process. This chapter concludes with the research questions associated with this study. The structure of this chapter is illustrated in Figure 2.1.

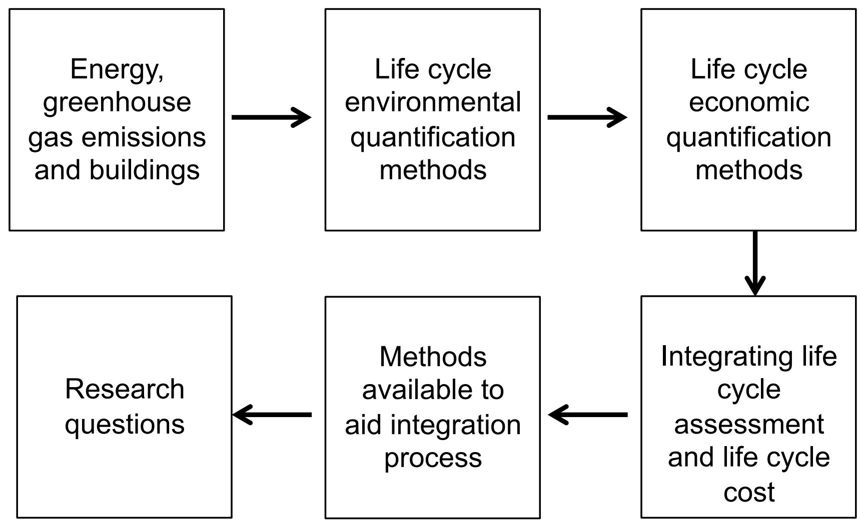


Figure 2.1 Structure of literature review chapter

2.2. Energy, greenhouse gas emissions and buildings

There is growing concern about the effect that buildings are having on the environment (IPCC, 2014; ASBEC, 2016) with construction being one of the most energy intensive sectors, and GHGE polluters, especially in developed countries (IEA, 2012). Over the years there has been an increase in efforts to understand the energy and GHGE consequences of the built environment. This raised awareness has led to the development of several forms of building evaluation that aim to analyse a buildings' environmental performance and suggest ways to reduce energy demand and GHGE (Haapio and Viitaniemi, 2008; Hopwood, 2009; Ng et al., 2013).

The focus has mainly been on the reduction of operational energy and GHGE of buildings, leaving the embodied energy and GHGE largely ignored (De Wolf et al., 2017) despite their potential significance. By way of example , embodied GHGE have been estimated to range between 10 to 97% of the total life cycle emissions for a building (depending on the building location, type, material use, assessment methods and assumptions) (Chastas et al., 2016). It has therefore become critical to consider a buildings' performance from a life cycle perspective.

These life cycle stages can be split up into embodied (which consists of extraction; manufacture, transport, construction, maintenance, demolition and disposal, depending on the system boundary) and operational (which related to the running of the building), as illustrated in Figure 2.2 below. In Australia, 20% of all GHGE are produced by the operation of commercial and residential buildings alone (Climate Works, 2013). These GHGE have been demonstrated to negatively contribute to the effects of climate change (IPCC, 2014) with growing emphasis placed on the need to implement mitigation strategies. These mitigation strategies mainly focused on the reduction of the direct (operational) emissions related to the running the building (such as heating and cooling).

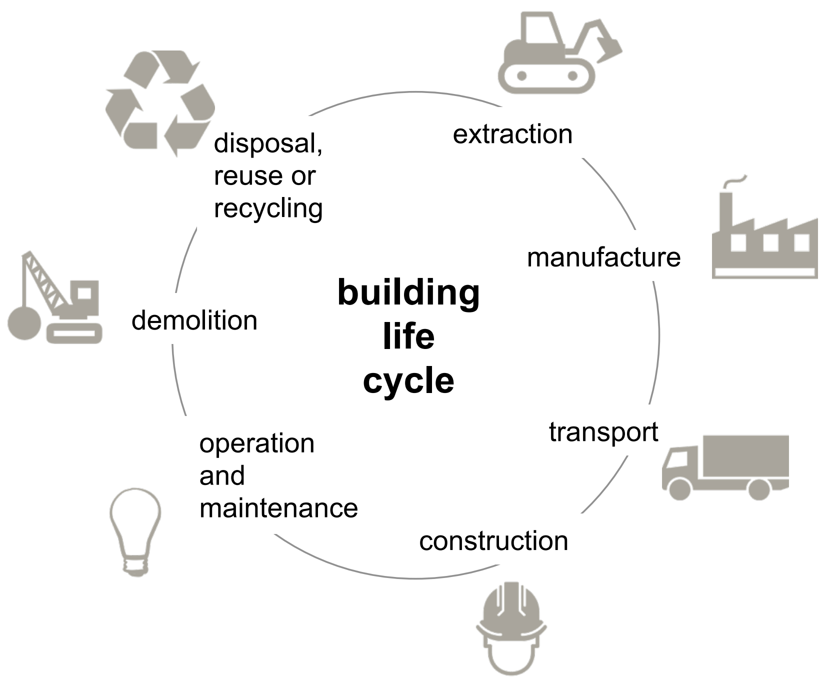


Figure 2.2 Life cycle stages of a building

Source: based on Crawford, 2011

2.2.1. Operational energy and greenhouse gas emissions

The operational energy and GHGE, which relate to the running of the building, have been the focus of industry and government. Voluntary standards and assessment methods, such as BREEAM (BRE, 2016) in the UK and Green Star (GBCA, 2016) in Australia, provide a framework and benchmark from which to prove a buildings environmental performance (which include aspects relating to a building's water use, GHG emissions and energy consumption, to name but a few). These assessment methods rely primarily on operational data to determine the overall performance of a building. Other measures such as Energy Performance Certificates and Display Certificates further aim to quantify and showcase a buildings operational performance. Several measures have also been taken to implement minimum standards and legislation. From a building regulation perspective, such as the UK's Part L 'Conservation of Fuel and Power' (2014), to a national perspective, with countries pledging to decrease their GHGE in line with set targets. The methods and tools available to quantify this life cycle phase have been discussed in more detail in Section 2.3.2.

2.2.2. Embodied energy and greenhouse gas emissions

Embodied energy and GHGE can be broadly categorised into initial emissions (such as the emissions related to the extraction and manufacturing) or recurrent emissions (such as the emissions related to the maintenance and replacement of building products) (Treloar, 1997; Dixit et al., 2010). Initial embodied energy (IEE) of a material is dependant on the type of material, quantity of material and the respective embodied energy coefficient (which is the value one can attach to a specific material to describe how energy intensive it is to manufacture). IEE is calculated by multiplying the quantity of the material by the energy coefficient and by the wastage factor (to account for the amount of materials wasted during construction).

Recurrent embodied energy (REE) refers to the energy requirements for maintenance, refurbishment, replacement and repair of building components during the life of the building. The replacement rate will be dependent on the building components being replaced. The weather, deterioration or obsolescence are factors that can affect the replacement rate. The REE has been demonstrated to represent between 32% (Treloar et al., 2000a) to over 70% (Stephan, 2013) of a buildings IEE.

There is presently no mandatory legislation requesting the assessment of embodied emissions, there is growing evidence that the international community is embracing the challenge of decreasing the embodied emissions associated with buildings. From the emergence of voluntary actions, where local city councils, such as Borough of Guildford in the UK, requests, as part of their planning requirements, the use of low embodied energy materials (Guildford Borough Council, 2011). To more mandatory actions, such as the Netherlands requiring the reporting of building material GHGE as part of their Dutch Building Decree (UKGBC, 2012). A number of Australia's local governments have followed suit and have set their own targets, such as City of Melbourne's Zero net emissions target by 2020, together with a strategy in place to create a carbon neutral city (City of Melbourne, 2014). However, detail as to the exact process of how embodied GHGE and energy is incorporated is not provided and rather vague references are made to 'more sustainable materials and construction processes' as a means of achieving net GHGE.

It is important to bear in mind that studies such as Säynäjoki et al. 2017, suggest that it is doubtful that LCA can actually produce reliable data for supporting policy-making in the building sector, due to the amount of subjectivity associated with it and the large amount of variance present in results.

To help counteract the inconsistent methodologies and incomparable datasets that plague embodied analyses, there has been a move to standardise the calculation procedure. Examples are the UK's PAS2050 (2008) Specification for the assessment of the life cycle GHGE of goods and services (Developed by the British Standards Institute, BSI) to the internationally recognized ISO 14040:2006 ISO 14040:2006 Environmental management – Life Cycle assessment: Principles and framework and ISO 14044:2006 'Environmental Management – Life Cycle assessment: Requirements and guideline. These standards are not mandatory yet and overall consensus on the correct approach must still be reached.

2.2.3. Operational life cycle stage focus

These operational focussed mitigation strategies, which often follow the energy hierarchy, as illustrated in Figure 2.3 below, emphasises the use of using passive measures (such as improving the building envelope through strategies such as insulation, shading and thermal mass) to decrease a buildings GHGE, followed then by active and generation measures ((Davis Langdon, 2013, Uqaili and Harijan, 2012; Sartori and Hestnes, 2007; Sadineni et al., 2011; Rackes et al., 2016)).

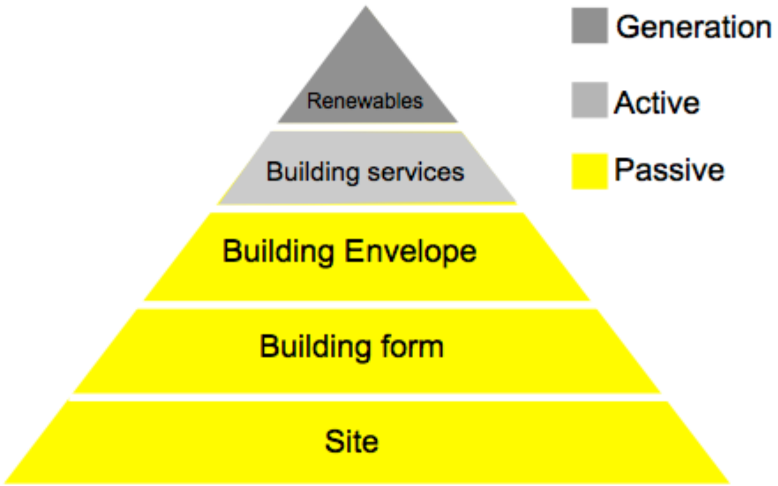


Figure 2.3 Energy Hierarchy

Source: Davis Langdon (2013)

Table 2.1 below lists some of the popular passive design strategies (PDS) used in Australia at present to lower operation GHGE (OGHGE) of residential and commercial buildings.

Table 2.1 Popular passive design strategies for residential and commercial buildings

Residential	Commercial
Insulation: Roof and walls[5, 6, 11, 12]	Insulation: Roof; wall[1, 4, 5]
Insulation: Floor[12]	Rain water collection[1]
Improved glazing: Double glazing; thermally broken glass[5, 6, 7, 12]	Improved façade performance[2, 4]
	Shading devices[2]
Internal shading: Curtains and pelmets[5, 9]	Integrated design[3]
External shading: Awnings[5, 9]	Improved materials selection[3]
Draught proofing[5, 11, 12]	Reduced water use[3]
Replace window frame[8]	Waste minimisation[3]
Apply solar control film to glazing[10]	Draught proofing[4, 5]
Orientation[12, 11]	Apply solar control film to glazing[5]
Improved material selection[5]	

Sources*:* [1] *Davis Langdon (2013)* [2] *Wilkinson and Reed (2006)* [3] *Australian Government: Department of the Environment and water resources (2007)* [4] *City of Melbourne (2013)* [5] *Beyond Zero Emissions (2013)* [6]*Australian Bureau of Statistics (2014a)* [7]*Edge Environment (2013)* [8]*Schneider (2015)* [9]*Environment Victoria (2013)* [10]*Australian Bureau of Statistics (2008)* [11] *McGee and Mosher (2013)* [12] *Wiltshire and Stock (2001)*

This focus on decreasing the operational emissions has left the embodied emissions largely ignored. The embodied emissions from materials and manufacturing, transport, maintenance and disposal have been estimated to make up another 11% of Australia's national emissions (Schinabeck and Wiedmann 2014). The embodied emissions have even been estimated to be as high as 70% for certain building typologies over its lifecycle (ASBP, 2014). The strategies employed to reduce the operational emissions are often resource and energy intensive to manufacture and implement on the building site (Dixit et al., 2010; de Wolf, 2014). Which often results in an increase in the embodied GHGE and consequently increasing the life cycle GHGE. The complex relationship between operational and embodied energy has been further explored by a study completed by Bunning and Crawford (2016), where it was found that the addition of external shading devices to an office building lead to a decrease in life cycle energy requirements by 24% for Melbourne. Thus demonstrating that the additional materials and consequent embodied energy required for the shading devices actually resulted in a smaller HVAC system being required which lead to a decrease in materials for the unit. As the operational emissions decrease the embodied GHGE (EGHGE) will start to signify a larger percentage of the overall life cycle GHGE (LCGHGE) in buildings (Crawford, 2011), and there is a greater need to explore this complex relationship further.

Several methods have been explored in literature to decrease the embodied energy and GHGE of PDS. Such as, decreasing the thermal resistance value (referred to as the R-value), with lower R-values having less embodied energy than higher R-value insulation (Karimpour et al., 2015). Different materials have also been explored, with the same study concluding that fibreglass has a lower embodied energy value than mineral wool, expanded polystyrene and polyurethane alternatives. A research project for ‘Low Embodied Energy Insulation Materials’ (LEEMA, 2013) has also explored different insulation materials, finding loose wood wool, cork and glass wool having lower embodied energy when compared to cellular (foamed) glass and extruded polystyrene. A method suggested to decrease the embodied energy of windows is to decrease the glazing area (Özkan and Onan, 2011) or changing the frame material (Mithraratne and Vale, 2004). To decrease the embodied energy of thermal mass it has been suggested using local materials or alternative materials such as rammed earth (Morel et al., 2001).

Other methods used to mitigate the embodied energy and GHGE of buildings include the use of recycled materials; decrease the size of the building and hence the quantity of materials; utilisation of more efficient construction processes (such as using more pre-fabricated items or machinery powered by renewable resources); extending a buildings service life; use of more robust and durable materials (which will decrease the amount of times a material needs replacing) (Pomponi and Moncaster, 2016; Crawford, 2011).

However just as focussing on the operational life cycle stage can have potential detrimental effects on the operational life cycle, so can just focussing on the embodied life cycle stage. By using methods such as decreasing the amount of materials or lowering the R-value, the operational GHGE/energy can possibly increase due to the thermal performance of the building being compromised. Thus it is vital to look at a buildings energy and GHGE performance from a life cycle perspective (including both the operational and embodied energy and GHGE performance). However, there are several barriers affecting the uptake of this life cycle perspective, as discussed in the next section.

2.2.4. Current barriers to life cycle approach

There has been an increase in studies looking at the life cycle environmental performance of buildings (such as Menzies et al. (2007), Petrillo et al. (2016), Treloar et al. (2000a) and Crawford (2013)), and an increase in tools available to assess this life cycle performance (such as SimaPro (2016) and eTool (2015)). However, environmental life cycle perspective has been slow to take hold, due to a number of barriers (Fouche and Crawford, 2015; ASBP, 2014). These include, for example, lack of consistent method, lack of reliable data, and lack of mandatory legislation (ASBP, 2014; Dixit et al., 2012a). The consistency in method (due to a lack of standardisation) and availability of comparable data (due to differing system boundaries and life cycle inventory methodologies) has been explored extensively in literature (Crawford et al., 2010; Ariyarante and Moncaster, 2014; De Wolf et al., 2015). The lack of legislation has been discussed briefly in the section above, and in studies such as Dixit et al. (2011) and Sturgis and Roberts (2010).

However one such barrier that has not been as widely explored is the uncertainty towards the financial cost of this life cycle environmental optimisation. Building decision-makers are unsure of the financial cost implications of this optimisation and design team members often don't have sufficient knowledge or appropriate tools to answer their concerns. An example of a study that has explored this barrier is Ariyarante and Moncaster (2014) who concluded that budget constraints are a key factor hindering the uptake of embodied carbon assessment. They further state that at present there is limited number of ways that cost benefit is demonstrated and that there is a need to demonstrate how the costs associated with embodied carbon can be quantified.

Another study completed in 2015 states that the capital formation cost relating to embodied emissions is not well understood and that in relative to operational emissions, it is much more difficult to measure and estimate the market value of embodied emissions (Wu et al., 2015). This study further emphasised that a perceived 'high price' (due to lack of demand and data) becomes a barrier, which is further compounded by human preference to value short term over long-term benefits. Langston and Langston (2008) looked at the relationship between embodied energy and cost from a Melbourne residential perspective, confirmed that consideration towards this would only be made if in the context of the initial project budget.

There have also been studies completed on the subject of the cost related barriers to low carbon or zero carbon buildings. Williams (2012) states that cost is an overarching barrier when it came to the uptake of low or zero carbon homes, smart technologies, low zero carbon community energy systems and low carbon tariffs. However, this study does not make direct reference to the inclusion of embodied impacts. Other such studies include Ellis (2009), Torcellini et al. (2014) and Catto (2008). Several studies have reported on the barrier of perceived extra cost to 'sustainable' or 'green' buildings. These studies include Kats (2003), Reed (2011) and Zalejska-Jonsson (2014). Again these studies do not make direct reference to the link between financial cost and embodied emissions.

Limited consideration of costs from a life cycle perspective is also a key barrier as financial decisions are mainly based on the initial cost, often not taking into account the future maintenance and operational costs (Jackson, 2008). The cost-effectiveness of low carbon solutions have become a critical issue for building owners and one of the main drivers behind their uptake (Ellis, 2009). Thus it has become vital to provide environmental and financial building analyses not only from an early design stage, so as to better inform design decisions (Braganca et al., 2014), but to also integrate the results in order to better understand their trade-offs. Several studies have aimed to integrate these two forms of assessment, namely using life cycle assessment (LCA) (either from an energy or GHGE point of view) and life cycle costing (LCC), and include examples such as Petrillo et al. (2016) and Savino et al. (2017), and have been discussed in more detail in Section 2.5 below.

2.2.5. Summary

There is a need to understand the environmental impact of buildings from a life cycle perspective. It will no longer suffice to minimise their environmental impact only from an operational point of view, which has been the focus of industry and government, or only from an embodied point of view, which may result in adverse effects on the operational stage. Approaching building evaluation from a life cycle perceptive will ensure that more comprehensive results can be achieved and more informed decisions can be made by homeowners, industry and government. Life cycle analysis, LCA, provides a useful tool for evaluating the environmental impact over the life cycle of the building and is discussed in more detail in the following section.

Continued emphasis should be placed firstly on improving the building envelope through PDS and then to implement active strategies, such as efficient heating and cooling. Followed by generation, such as renewables. By following the energy hierarchy, designers can decrease the need for large and inefficient active systems as the passive strategies would have decreased the energy needs.

There has however been slow uptake of building strategies that consider both the operational and embodied GHGE. Several barriers hinder the uptake of life cycle energy and GHGE reduction strategies, including the lack of consistency of method, unavailability of comparable data and the attitude of the government. These barriers have been well documented in the literature (for example Menzies et al. (2007), Dixit et al. (2012a); Farhan et al. (2014); and Ariyarante and Moncaster (2014)). However, one of the remaining barriers is the uncertainties of the financial cost, has not been as widely explored. Homeowners and project developers are unsure of what the cost implications of the inclusion of both operational and embodied emission reduction strategies into their project may be and design team members do not have sufficient knowledge or appropriate tools to address these cost concerns. Ariyarante and Moncaster (2014) reaffirm this problem by stating, “there is a need to demonstrate how costs associated with embodied emissions can be quantified”. Wu et al (2015) further emphasises that the cost relating to LCGHGE is not well understood.

The limited amount of available research on this subject has explored either embodied GHGE in isolation, without considering the potential impact on the operational GHGE if the embodied emissions are lowered (Ariyarante and Moncaster, 2014; de Wolf, 2014), or cost in isolation (Morrissey and Horne, 2011; Gluch and Baumann, 2004). Several studies have also only concentrated on one life cycle phase, such as the relationship between capital cost and embodied emission reduction (Langston and Langston, 2008 and ASBP, 2014), ignoring the potential impact on other costs (such as running and maintenance costs). In order to combat this the financial evaluation tool LCC can be used, which will compliment the life cycle perspective from LCA, as discussed in more detail in the following section.

The next two sections discuss the methods available to quantify the life cycle environmental and economic performance of buildings.

2.3. Quantifying life cycle energy and greenhouse gas emissions of buildings

Buildings involve the consumption of natural resources and have a significant impact on our environment. From the materials that they require which is extracted from earth, to the significant amount of water needed during the construction and operation stage of the building and to the subsequent GHGE released throughout its life cycle. There is a need to quantify a building's environmental impact so as to better understand what the implications of the built project will be and to minimise this impact.

Over the years methods available to assess the environmental performance of buildings have increased. Bragança et al. (2010) classifies these methods according to three categories: Systems to manage building performance (Performance Based Design); Sustainable building rating schemes and LCA. The first category, Performance Based Design, is an approach to building-related processes, products and services and aims to ensure that the 'end' result meets the design objectives. This approach requires a detailed understanding of the entire supply, installation and maintenance chain, which can make it quite a time consuming and costly method (Bragança et al., 2010; Williams, 2016).

The second category, sustainable building rating schemes, assists in the translation of a sustainable goal into specific objectives (often in the form of a checklist) for the evaluation of the overall performance. Examples include BREEAM (BRE, 2016) and LEED (USGBC, 2016). These rating schemes are dependant on the regional standards and legislation of their respective countries of origin, rendering them not widely applicable to all building designs. Other disadvantages include the different weighting criteria applied to different categories (therefore one criteria will be more prominent than another), differing system boundaries and differing benchmarks (Haapio and Viitaniemi, 2008). Another major disadvantage is that the performance of each life cycle stage is either not included or not as evident to the user. Rating tools, such as LEED, have only now started including the embodied energy and GHGE as part of their assessment, and the baselines for benchmarking have not been defined yet (de Wolf, 2014). There is also a tendency for these rating tools to focus on one life cycle stage, namely operational (Murugan and Kato, 2010; Kats, 2003). Even though the operational stage often reflects the largest contributor to energy use and GHGE, other life cycle stages have a significant contribution when the building is considered from a whole life cycle perspective. There is a need to ensure that the impact from one life cycle stage does not negatively affect the impact from another life cycle stage (Crawford et al., 2010).

The third category, LCA, provides a method of assessment that includes all life cycle stages and is often viewed as a comprehensive and systematic approach to environmental evaluation, appropriate to building assessment (Alshamrani, 2016; Ramesh et al., 2010; Cabeza et al., 2014; Ortiz et al., 2009). This form of building assessment is quite data intensive and time consuming, however, it provides a more holistic form of assessment when it comes to both operational and embodied energy as well as GHGE (Bragança et al., 2010). The section below describes the LCA approach in greater detail.

2.3.1. Life cycle assessment

LCA is a method for evaluating the environmental impacts of products holistically, including direct and supply chain impacts (Lenzen et al., 2014). LCA helps to analyse the relevant inputs (such as water, energy and raw materials) a product or building requires over its multiple life cycle stages in relation to its outputs (such as atmospheric emissions, waterborne and/or solid wastes).

2.3.1.1. Types of life cycle assessment

Depending on the projects aims and requirements, three main types of LCA can be used, namely a conventional (baseline) LCA, comparative LCA or streamlined LCA, as described in ISO 14040 2006.

Conventional life cycle assessment

Conventional LCA, also known as baseline LCA, is used to assess an individual product, system or process and to help identify the most significant environmental impacts associated with that product, system or process. These significant impacts can then be targeted and improved upon. It is often used internally to aid product development, in order to improve upon the environmental performance of a product.

Comparative life cycle assessment

This LCA method is used to compare the environmental performance of two or more products or processes that have the same function. This method will help the user to identify and select the product with the lowest environmental impact. The functional unit is very important in this type of analysis and needs to be the same for all products being assessed. This method usually starts with a conventional LCA for the individual products being assessed, and a comparative assessment will take place to identify the best option.

Streamlined life cycle assessment

LCA performed on a product can include multiple environmental impacts (including energy, waste and GHGE, for example) and several life cycle stages (for example raw material extract, operation and demolition). This analysis can be quite time and data intensive and studies will often have a specific goal (for instance only requiring the GHGE), not requiring a full LCA for every environmental impact. This type of LCA, where the scope is limited (in depth, breadth and detail) is referred to as a streamlined LCA. A streamlined approach, for example, that considers only the energy-related environmental impacts is commonly referred to as a life cycle energy analysis (LCEA) (Cooper and A.Fava, 2006). It is important to identify the goal and scope of the analyses at the start of the study to aid interpretation of results and help decrease any misinterpretation (as to what has been included or excluded).

2.3.1.2. Life cycle assessment standards

In order to consolidate and standardise the life cycle assessment approach the International Organisation for Standardisation published the first LCA standard in 1997. There have been several subsequent iterations of this standard, the latest being released in 2006 with the 'Environmental Management – Life Cycle Assessment – Principles and Framework (ISO 14040, 2006) and 'Environmental Management – Life Cycle Assessment – Requirements and Guidelines' (ISO 14044, 2006). Another standard gaining more relevance, especially in Australia with its recent launch (2014), is the 'Environmental Performance Declaration' (EPD), a form of conventional LCA, which provides a snap shot of a products' environmental performance with regards to energy, GHG and other environmental impacts. It is based on the 'Type III Environmental Declarations' Standards (ISO 14025). Another LCA standard, created by the European Committee for Standardization (CEN) is the TC350, makes reference to five types of performance (environmental, social, economic, technical and functional), and is based on EN 15978 (2011) and EN 15804 (2012).

Recent research has highlighted some of the shortcomings of these international standards, such as ill-defined system boundaries and unfairly justified inputs and outputs (Dixit et al., 2012b). By way of example, impacts categories and inputs of study have to be defined prior to the study, however it is difficult to determine whether individual inputs and outputs will have a significant impact prior to data collection (Crawford et al., 2011). In addition, as Säynäjoki et al. 2017 states, that these standards should be comparable and compatible with each other but consequently lead to differing results due to the inherent differences in the approaches, the subjective and objective choices and assumptions made by the assessor and the availability of data.

2.3.1.3. Life cycle assessment framework

According to the ISO 14044 standard, as mentioned above, there are four fundamental steps for conducting an LCA: define goal and scope (also referred to as the system boundary); inventory analysis (also referred to as life cycle inventory); impact assessment and interpretation. The following section will briefly explain each step as depicted in Figure 2.4 below.

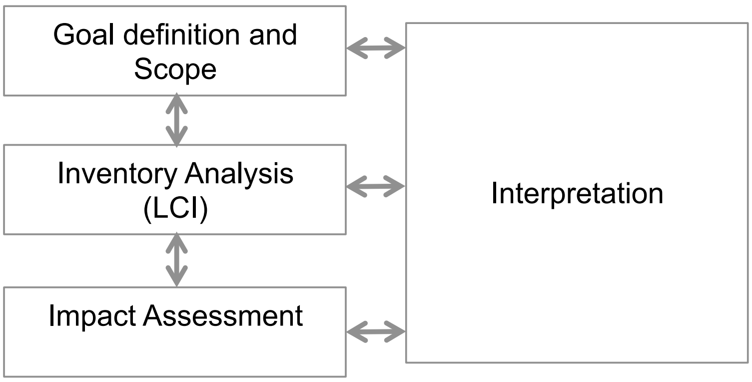


Figure 2.4 Life cycle assessment framework steps

It is important to be aware that the LCA process should be an iterative approach, where each phase relies on, and can also provide feed back to inform, the outputs of the previous phase (Crawford, 2011). The practitioner has to identify gaps and be able to revisit aspects of the study in order to further refine and focus the study. The steps below are listed in order of sequence it may become necessary to revisit each step as the study progresses.

Step 1: Goal and scope definition

This first step is vital to any LCA study as it defines the intention (goal) and the extent (scope) of the study. The following terms form part of the vocabulary of this step:

Goal

The goal will direct the course of the study and highlight the intended use of the study's results. For example, the goal of the study can be to look at the GHGE of a product only so as to afford a decision maker the opportunity to select the product with the least amount of GHGE.

Scope

The scope should complement the goal and must determine the life cycle stages and boundaries that have to be considered in the study. The scope must state what inputs, outputs and impacts are included and excluded, and the reasons for inclusion or exclusion. A streamlined LCA approach, as mentioned earlier, can help limit the scope of the study in order to aid ease of analysis (as stated before, a full LCA can be quite complex and time consuming as there are multiple environmental impact categories and life cycle stages and not all of them are needed for the study goal of each study).

System boundary

A product system consists of multiple individual inputs. The system boundary compliments the scope by defining the inputs, outputs and process that are to be included in the study. Inputs can include raw material, intermediate materials, energy, and water, for example. Outputs may include atmospheric emissions and water and land pollution. Essentially, it states how far upstream (for example the manufacture of materials) and downstream (for example, the operation and maintenance) the study will go (Treloar, 1997). Common system boundaries used is cradle to gate (from resource extraction to the factory gate), cradle to grave (from resource extraction to disposal phase) and cradle to cradle (from resource extraction to disposal phase which includes recycling). The inputs and outputs depend not only on the goal of the study but also on the available data.

Functional Unit

This refers to the unit of reference and is essential to comparative LCA studies to ensure that comparisons and conclusions are drawn on a common basis. The functional unit will depend on the function or application of the product or process. In order to aid ease of analyses it is suggested that a unit that is easily understandable be selected for the functional unit (Crawford, 2011).

Step 2: Life cycle inventory analysis

The life cycle inventory (LCI) is a collection of the data and calculations of all the inputs and outputs related to the product or system. This step involves, based on ISO 14044, involves inter alia drawing specific process flow diagrams, outlining unit processes to be modelled, listing the data categories, defining the unit of measurement. This step is often seen as one of the most time and cost consuming aspects of the LCA process (Crawford, 2011). LCI is often presented in datasets, such national public databases (such as ATHENA, from the US), or commercial databases (such as Ecoinvent, from Switzerland). These LCI datasets are compiled with the following methods: process, input-output or hybrid analysis.

Process Analysis

This is a bottom-up technique in which the resource requirements and pollutant releases of the main production processes are assessed in detail (Lenzen, 2002). This data is based on actual measured data specific to that product or process. This method is very dependant on available data and the time and budget there is to compute a large amount of data inputs (as process analysis can be labour and time consuming). The output of this method is also dependant on the reliability and age of the data (often supplied directly by the manufacturer). Several LCI datasets are preformed based on this method (Monahan and Powell, 2011) and include examples such as Bath University's Inventory of Carbon and Energy (ICE) (Hammond and Jones, 2008). Several standards, such as RICS (Sturgis and Roberts, 2010), suggest the use of the ICE data when calculating embodied emissions. Process analyses can be convenient and provide accurate and relevant information for the particular product or process being analysed. However, it is important to note that this popular method suffers from a major 'truncation error, which can omit up to 87% of the embodied energy of a product (Crawford, 2008). This is due to the fact that the product system has a finite boundary and can lead to the omissions of contributions outside this boundary.

Input-Output Analysis

Input-Output (IO) analysis is a top-down macroeconomic technique that uses sectoral monetary matrixes describing complex interdependencies of industries (Treloar et al., 1999). The data is complied in IO tables, which describe the input required by each economic sector from each and every sector in order to produce a certain quantity of outputs (Crawford, 2011). These tables help demonstrate the whole economic activity at a national scale. This method is regarded as more comprehensive than process analyses and takes into account many upstream and indirect effects. However, IO depends on a high level of aggregation (i.e. 'aggregation error') and cannot convey simple processes due to the use of a 'black box', which confines the mechanism behind results (Crawford, 2011).

Hybrid Analysis

This approach combines both process and input-output analysis. By combining both methods, the problems associated with each individual method can be improved upon as a whole. According to Lenzen et al. (2004), there are three different hybrid categories. These includes ‘tiered hybrid analysis’ (the direct and downstream requirements and some important lower order upstream requirements of a product system are examined in a detailed process analysis and the remaining higher order requirements are analysed with IO analysis); ‘IO based-hybrid analysis (IOH)’ (important IO sectors are further disaggregated once more detailed sectorial economic data becomes available, also known as Path Exchange hybrid) and ‘Integrated hybrid analysis’ (process-based system represented in a technology matrix by physical units per unit of operation time of each process while IO system is represented by monetary units).

However, it is important to be aware of the uncertainty and variation associated with embodied energy data, with a ±20% uncertainty range for process data and ±50% range for input-output based data (Stephan et al., 2013; Crawford, 2011).

Step 3: Life cycle impact assessment

Life cycle impact assessment (LCIA) translates the previous steps LCI analysis into numerical indicators for specific categories to determine the magnitude and significance of a potential environmental impact. Common impact categories include global warming; depletion of minerals and fossil fuels; photochemical oxidation; human toxicity; ozone depletion; eutrophication; water use; land use; acidification and ecotoxicity (Crawford, 2011).

The LCIA assessment, as based on (Crawford, 2011), includes the following:

- Selection and definition of impact categories
- Classification (classifying inputs and outputs according to the impact categories)
- Characterisation (converting the LCI results into common units)
- Normalization (expressing the magnitude of the impact factors on a scale common to all assessed categories)
- Grouping (sorting the impact categories into specific areas)
- Weighting (assigning weights or numerical values to the different impact categories based on perceived importance)
- Data quality analysis (verifying the accuracy of the results)

Steps such as ‘weighting’ are very subjective and the importance of the impact will depend on the assessor. It is important to approach this step with transparency and make clear what assumptions have been made.

Step 4: Interpretation

The final step requires the combination of step 2 (LCI) and step 3 (LCIA) in order to determine the most significant inputs, outputs and potential environmental impacts of the product or process studied. Data and results should be qualified, checked and evaluated to determine areas of improvement and to highlight any limitations inherent in the study. A method often employed in this step is called sensitivity or uncertainty analysis, and will be explained in more detail in Section 2.3.6.1.

2.3.2. Methods available for operational energy and greenhouse gas emission analysis

The operational energy and GHGE performance of a building can either be calculated either with manual equations or with dynamic simulation. The manual equations (also known as static equations), such as the empirical method suggested by ASHRAE (ASHRAE, 2010), allows for the quick estimation of the expected heating and cooling loads of the building. These calculations are based on building physics and ‘rules of thumb’ and rely on average building characteristics and climatic data. These equations require several data inputs, often not available at an early design phase (which has been suggested to provide to most appropriate platform from which to suggest and implement sustainable design solutions (Braganca et al., 2014)) and can be quite time consuming and resource intensive. An example of a study that used manual calculations for their operational energy building performance was Stephan et al. (2012).

Dynamic simulation is based on the same building physics principles used for the empirical method, and is performed with the use of commercially available software. A building is virtually duplicated in a software program with internal databases, default values and calculations, which can then be used to predict the operational energy and GHGE performance of a building based on data inputs such as building shape, materials, orientation, use and occupancy. Most of these variables are known at an early design stage (Braganca et al., 2014). These programs have been noted to accelerate the design process and optimise the building performance with relatively low cost (Wang et al., 2016). Several sustainability-rating schemes, such as LEED and Green Star, recommend the use of approved tools in order to achieve the targeted rating. Multiple tools are available for use, with extensive research done in comparing each tool's performance and industry preference (Crawley, 2008; Sterner, 2011; Reeves et al., 2012). EnergyPlus (U.S DOE, 2016), which is based on the heat balance approach and conduction transfer method. It is widely acknowledged as the most accurate software for predicting the heating and cooling loads in a building (Wang and Zhai, 2016; Stavrakakis et al., 2014). EnergyPlus however requires numerous data inputs (which might not be known at an early design stage) and expert training to use the complicated user interface (Østergård et al., 2016).

Integrated Environmental Solutions (IES) Virtual environment is a popular industry tool with an integrated suite of applications linked by a common user interface and a single integrated data model (Crawley, 2008). It is easy to use but it does require training and can be quite time-consuming dependant on the complexity of the model. Other tools include eQuest (Hirsch, 2016) which uses the same operating system as EnergyPlus, DOE-2, which is an analysis tool which is easy to use and performs an hourly simulation of the building (based on walls, windows, glass, people, plug loads and ventilation) and Transient system simulation program (TRNSYS) which implements a component based approach. However, similar to eQuest, TRYNSYS does not have much popularity amongst industry professionals (Sterner, 2011).

A cloud based energy simulation tool that is gaining popularity is Green Building Design Studio (GBDS) (Autodesk, 2013). It is seamlessly integrated with Revit (Autodesk, 2016), a popular building design tool within industry and is often quoted as the "current market leader" (Egger, 2015), making energy analysis accessible with a tool most architects and engineers use already (Autodesk, 2013). It uses the model of the building built in Revit, which includes all the thermal properties of the building elements needed for GBDS. The model is then exported as a Green Building Extensible Mark-up Language (gBXML) and uploaded on the GBDS website portal. It has been validated by ANSI/ASHRAE 140 and certified by the U.S Department of energy and uses a DOE-2.2 simulation engine. Exporting CAD or building new models in other simulation programs can sometimes be "fairly difficult, complex and require special training" (Adams, 2013). GBDS can simplify this process as only one model needs to be built (i.e. in Revit) and then uploaded where a variety of building features are tested automatically. GBDS is easy to use and is suitable for decision-making made early in the design stage (Stumpf et al., 2011). However, each tool has its own inherent flaws. GBDS has been found to occasionally underestimate the annual heating energy demand when compared to measured data (Reeves et al., 2012).

It is important to note the limitations of each tool. Each tool has a series of assumptions and default settings inherent to its architecture that have to be discussed and the sensitivity of the results checked. It has also been noted that often each tool can provide slightly different results for the same building (Reeves et al., 2012; Crawley, 2008). These tools also fail to consider the effect that operational improvements, for example insulation and glazing, have on the impacts associated with the other stages of the building life cycle, such as the manufacturing stage (Crawford et al., 2010). These tools often focus only on the operational life cycle stage, excluding the embodied life cycle stage.

2.3.3. Methods available for embodied energy and greenhouse gas emission analysis

Similar to the operational life cycle performance, the embodied performance of a building can be quantified either manually or with the help of simulation software programs.

There has been an increase in the number of tools and software available to aid calculation. From commercially available tools, such as SimaPro (Netherlands); GaBi (Germany); Boustead (UK) and eTool (Australia), to in-house developed data and tools, such as Arup's Project Embodied Carbon & Energy (PECD) dataset that consists of Arup projects with data extracted from Revit models. Each tool employs inventories that include the embodied energy coefficients of building products and materials. The origins of these datasets ranges from ICE (UK); Ecoinvent (Switzerland) and AusLCI (Australia), to name but a few. Most of these datasets provide data from cradle to gate (resource extraction to factory gate). Several researchers have analysed and compared these available tools and have outlined their advantages and disadvantages (Ariyarante and Moncaster, 2014; De Wolf et al., 2014). The outcome of these comparisons often reflect some of the same characteristics that plague LCA as mentioned earlier, due to inconsistent calculation methodologies and system boundaries resulting in a range of reported embodied energy figures dependent on what tool is used. In addition to this, several upstream phases are left out of the calculation because of the reliance on cradle to gate data only (instead of cradle to cradle, i.e. resource extraction to re-use), resulting in a measure of incompleteness which has been shown to be 50% or more (Crawford, 2008).

Manual calculations will depend on the approach selected, which, as described above, include process, input-out or hybrid. Examples of the manual calculations used for the process method can found in Hammond and Jones (2011) and RICS (2012). An example of for input-output calculations can be seen Lenzen et al. (2003). Crawford et al. (2016) provides an example of calculations used for input-output based hybrid approach. Even though manual calculations are quite time consuming and data intensive, they provide greater transparency as to the inputs and data being used and help negate the effect of the 'black box' often associated with some of the simulation tools described above (Athanassiadis et al., 2015).

2.3.4. Life cycle energy assessment

As stated before streamlined LCA is often used to narrow the scope in order to make it specific to the query being investigated and more manageable to the assessor. Environmental related streamlined LCA will often be focussed on either the energy or the GHGE. A brief description of life cycle energy analysis (LCEA) and life cycle GHGE analysis (LCGHGE) and the relevant studies concerning both, is set out below.

LCEA accounts for all energy inputs to a building during its life cycle (Cabeza et al., 2014). LCEA includes embodied energy (the energy content of all materials and processes used in the building throughout its life cycle from extraction, construction, maintenance and demolition), operational energy (energy required to run the building including heating and cooling to domestic hot water, lighting and appliances) and demolition energy (the energy required at the end of a buildings useful life, inclusion of transportation to landfill site or recycling plants). The consumption of energy has been one of the greatest environmental impacts of buildings (Crawford, 2011). Accordingly, much focus has been placed on improving the energy efficiency of building projects with LCEA being a popular tool to help evaluate building projects.

There are several studies that use LCEA, such as those listed in Saynajoki et al. 2017. An example that demonstrates the use of LCEA is a study completed by Stephan and Stephan (2016) that examined at the life cycle energy of a residential building in Lebanon. Their study assessed 22 energy reduction measures in terms of life cycle energy saved over a 50-year lifespan. The life cycle energy stages that were considered included IEE, REE, primary operational energy, direct transport energy and indirect transport energy. Demolition energy was not included. Their embodied energy calculation was completed manually with the use of an IOH approach. Operational energy was estimated with thermal dynamic software using DEROB-LTH. Energy reduction measures included installing hot water collectors, insulation, LEDs and PV. Their study concluded that embodied energy was the most difficult energy demand to reduce while conserving the same functional unit. There were also several design limitations to the existing building analysed, with no allowance for drastic change of materials or change in design that would decrease the embodied content. Measures relating to decreasing the operational energy resulted in greater life cycle energy (LCE) savings. The LCE demand of the assessed building could be reduced by 43% with the specified energy reduction measures.

Another example is an Australian based study completed by Crawford et al. (2010) that analysed the life cycle energy associated with eight standard residential construction assemblies over a 50-year period. Their study included initial and recurrent embodied energy and operational energy. Demolition energy is not considered due to the fact that it has been estimated to represent less than 1% of the building's life cycle energy requirement. Embodied energy was calculated manually with the use of IOH approach. Operational energy was estimated with the software program TRNSYS. Their study demonstrated that even though a particular assembly may have higher IEE requirements than another, the potential for improved thermal performance of that assembly and reduced replacement rate may result in a lower net energy requirement of the life cycle of the building. Their study also demonstrated the usefulness of LCEA for comparative analysis, where the LCE of one building assembly can be compared against another so as to identify the one with the lowest overall environmental impact.

2.3.5. Life cycle greenhouse gas assessment

Life cycle GHGE (LCGHGE) analysis, also referred to as life cycle carbon footprint (LCCf) analysis, is similar to LCEA described above but only relates to the GHGE released during the life cycle of the building. From the EGHGE (the emissions released during the extraction, manufacturing, maintenance and demolition) and OGHGE (the emissions released through systems associated with running the building).

An example of a UK based residential study that looked at the LCCf is Schwartz et al. (2016). They used a multi-objective genetic algorithm (MOGA) to find optimal designs for refurbishment over a 60-year life cycle. The initial embodied carbon was calculated by multiplying the energy coefficient (EC_m) by the density (Di), thickness (Ti) and wastage factor (W_m). Operational carbon was quantified through EnergyPlus. Recurrent carbon was not included in the calculation.

Their study used LCCf to demonstrate the relationship between operational and embodied carbon (see Figure 2.5) depending on the refurbished strategy selected. The graph illustrates that for the Waste combustion district heating (WCDH) option (which is a 'very efficient heating energy source'), the embodied carbon is between 20% and 30% of the overall LCCf. Their studied demonstrated that refurbishing a building would save a significant amount of CO_2 compared to a new building. The amount of CO_2 saved would also depend on the type of refurbishment.

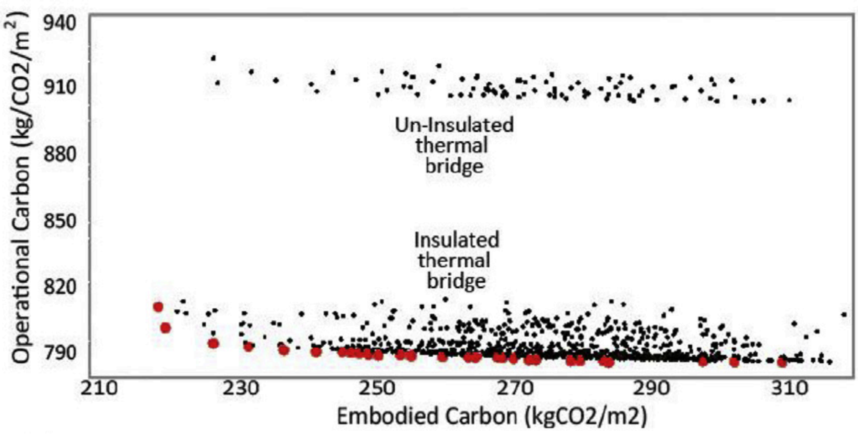


Figure 2.5 Embodied and operational carbon of energy efficient measure WCDH

Source: Schwartz et al. (2016)

Another UK based study that examined the LCCf of refurbished schools was done by Bull et al. (2014). The embodied carbon coefficient was obtained from the process based database, ICE from Bath University. The initial carbon was calculated similar to the above methodology. They concluded that from a life cycle point of view, the operational carbon represented the largest percentage.

2.3.6. Limitations of life cycle analysis

LCA is a subjective and iterative approach and as highlighted above is plagued by a significant amount of uncertainty. With such uncertainty, a significant amount of limitations and barriers are present to any life cycle study. Notwithstanding the standards, such as ISO 14044, that help rationalise the process it is important to be aware of the multiple parameters that affect the LCA approach, process and results. Some of these parameters, as provided by Dixit et al. (2012b) and Crawford (2011) include the following:

Regulation and standards

LCA is still in a state of constant development and refinement. International standards, such as the ISO 14044, help regulate the LCA methodology. However, these standards still require further refinement as “its selection criteria seems practically impossible without models containing loops” (Lenzen et al., 2004), As mentioned earlier, the ISO standard requires of the assessor to draw a boundary around the processes without full understanding of the environmental impact as a whole. There are also no mandatory regulations enforcing the use of specific LCA methodology. This, coupled with the fact that there is also great variety in terms of data methods (from process, to IO to hybrid) being used in calculations, causes significant variations in results across life cycle studies.

Differing system boundaries

Not all studies assume the same scope and they either include or exclude significant upstream or downstream impacts. Two LCA’s of the same product may assume differing system boundaries and resulting in different outcomes (Lenzen et al., 2004; Monahan and Powell, 2011, Heinonen et al. (2016).). Treloar et al (2000) has identified that the most common exclusions in LCA are ancillary activities (for example administration); inputs from services (such as banking), further processing of complex materials and non-feedstock energy to make fuels. One method to counteract the neglect of several upstream processes is the use of IO or Hybrid data sets, instead of process on its own, to calculate more holistic LCA results.

Geographic location

Data can vary depending on location (due to aspects like climate, fuel mix and fuel price, etc.). For example, if a country has a greater percentage of its energy production extracted from renewable resources, the embodied and operational emissions related to the production of that material may lower. The geographic location affects the environmental impact and importance (and therefore weighting) of impact categories. Studies that rely on data from other areas can thus cause errors and misinterpretation of results.

Data issues: source, age and completeness

LCI involves the collection of a vast amount of data from a variety of sources. Different data sources have unique approaches and subjective selection of data influences. The age of data can also affect if it accounts for new technological advances (for example some IO tables are only produced every few years and can become out of date quickly) (Dixit et al., 2012b). The completeness of the data can depend on whether the studies had access to primary data sources, or rely on secondary data sources, which can affect the interpretation of the assessor. Other aspects that affect data are availability and reliability of source of data.

Lack of knowledge and awareness

LCA has had a slow uptake within industry caused by the lack of mandatory regulations that require it and minimal financial incentives (Crawford, 2011). Awareness of the suitability of LCA as a tool for evaluating environmental impacts has been limited. However, with the public and private environmental consciousness continuously evolving, and the life cycle approach to building assessment is starting to gain more traction. This can be seen with the launch of EPD in Australia in 2014 as well as other countries, with environmental assessment methods such as Green Star incorporating credits relating to Life Cycle Assessment.

Time and cost-intensive

LCA is often criticised as a time consuming exercise that is expensive to perform. The data collection, especially for Step 2's LCI, requires a significant amount of time to collect and is often a quite complex and difficult task due to either limited availability of data or difficulty in gaining access to manufacturer specific data.

Interpretation

As stated earlier, LCA is a subjective exercise and results being dependant on the assessors' assumptions and decisions. Step 1 is dependent on the assessor's goal of the study and the subjective choice of system boundary selected (Lenzen et al., 2004). LCIA requires the assessor to assign weighting to the impacts, deciding on the relative importance of one impact over the other another. Interpretation of the steps is significantly influenced by the assessor's knowledge and understanding of the results.

2.3.6.1. Dealing with uncertainties in life cycle assessment

As stated earlier LCA studies involve multiple steps and are very dependent on the availability of data and the assessor's assumptions. Due to the subjective nature, a large amount of uncertainty is inherent in any LCA study (Crawford, 2011, Säynäjoki et al. 2017). Sensitivity analysis is a popular technique used in life cycle studies to help highlight the inputs and assumptions that affect the study results most significantly. It involves making minor changes to key variables in order to observe the effect on the outcome originally predicted (Langston, 2005). The value of key variables are adjusted one at a time in order to check the sensitivity of the results (Ashworth and Perera, 2015).

There are several methods to available for this, such as the One-at-a-time (OAT), Monte Carlo technique and interval analysis. Most methods either fall into the deterministic category (where values are selected for one or more parameters and the rest of the values remain constant) or probabilistic (where parameters are assigned a probability distribution). Studies such as Groen et al. (2014), Heijungs and Huijbregts (2004) and Budavari et al. (2011) provide a detailed overview of the various sensitivity analysis techniques available for LCA, with the Table 2.2 providing a brief overview of some of the available methods. The methods discussed are related more to quantitative studies, due to the nature of this study's research.

Table 2.2 Sensitivity analysis methods

Sensitivity analysis method	Detail	Sources
One-at-a-time approach (OAT)	Subject of the input parameters are changed one at a time to see how much they influence the results. Advantages: Easy to perform and to understand, can be used for smaller data sets. Disadvantages: Time consuming; might not consistently take all parameters into account.	Groen et al. (2014)
Monte Carlo analysis	Executed by means of taking large numbers of random parameter values based on their probabilistic distribution. Advantages: Takes into account a large number of parameters. Disadvantages: Problem in defining the distribution of the input parameters, large number of input probability unknown; requires a large number of assumptions; time consuming, needs the model to be run a number of times; limited for simple models and data intensive.	Groen et al. (2014) Heijungs and Huijbregts (2004)
Scenario analysis	Calculating different scenarios to analyse the influence of discrete input parameters Advantages: Easy to perform and understand. Disadvantages: Result based on the scenario selected.	Budavari et al. (2011)
Interval analysis	Consists of providing a range of values for each input parameter instead of a single value. Output provided in the form of an interval. Advantages: Easy to perform and understand; applicable to early stage design analysis where not	Moore and Bierbaum (1979)

Sensitivity analysis method	Detail	Sources
	a lot of information is known. Disadvantages: Requires assumptions to be made.	
Matrix perturbation (MP)	A method of local sensitivity analysis. Makes use of the first order of partial derivatives, which can be converted into relative multipliers (if a multiplier is larger the result will be more influenced by that input). The result of this method shows how much the results will change if the input parameters are slightly changed (perturbed). Advantages: Can analyse slight changes; useful for large models as a precursor to more computationally demanding methods. Disadvantages: Result only holds for small changes around the original parameter values.	Groen et al. (2014); Heijungs and Suh (2002)
Method of elementary effects (MEE)	Ranges of the individual parameters are taken into account (with a upper and lower boundary selected). MEE can be seen as an extension of OAT. Advantages: Easy to perform; complements OAT. Disadvantages: Results not an estimation of the actual variance decomposition.	Groen et al. (2014); de Koning et al. (2010); Mutel et al. (2013)
Sobol' sensitivity index	Assigns a sensitivity measures to each input parameter by calculating how much of the output variance can be allocated to each input parameter. Advantages: Allows for the calculation of the interaction effects and the total effect index; provides the variance. Disadvantages: Requires many runs to calculate indices and thus the model is computationally expensive.	Groen et al. (2014); Sobol (2001)

Monte Carlo analysis, which can be traced back to the 1930's, uses probabilistic distribution of parameters to generate thousands of results, which in turn represent the probabilistic distribution. It is a popular probabilistic sensitivity analyses technique, especially in physical sciences, engineering and computational studies. As with other probabilistic methods, Monte Carlo is very time and data intensive and requires the assessor to have a good understanding of probabilistic distributions.

Deterministic methods values are varied manually to test the sensitivity of a study's outcome. These methods are simpler to compute than probabilistic methods and suited to LCA studies. Interval analysis is good for early stage design when not a lot of information and detail is available about a project. Results can then be presented in variation and percentages (Moore and Bierbaum, 1979), not placing an emphasis on one single value but rather presenting a range of possible results. Scenario modelling is useful in acknowledging that there are several possible scenarios, with more than one variable affecting the results at any given time. There are two main categories of scenario modelling, being 'what-if' (which explores future scenarios depicting what would happen to the results 'if' that scenario was assumed such as 'high or low fuel price' or 'high or low renewable energy uptake') and 'corner stone' (which does not provide quantified results rendering it unsuitable for comparative LCA studies).

Though it is evident that there are multiple approaches to sensitivity analysis there is no single correct method of performing sensitivity analysis (Flanagan et al., 1989). The method selected will depend on the nature of the study and the knowledge of the assessor. Regardless of the approach, it forms a vital part of life cycle studies as it is paramount to address the inherent uncertainty that plague these studies. Sensitivity analysis will make the study more transparent and help to potentially decrease misinterpretation of results.

There are also several methods to illustrate uncertainty in graphs. Error bars are one of the most common graphic examples and used in several studies such as Stephan and Stephan (2016) and Crawford et al. (2016), refer to Figure 2.6. The amount of error is represented by the length of the error bar line and usually plotted for each point. Error bars are more suited for line, bar or column charts, where caution should be paid when using them for graphs such as scatter plots where there are numerous data points and error bars will not be as visible. For scatter plots it is recommended that the uncertainty be represented by a shaded area such as a circle or rectangle surrounding each point to indicate uncertainty (Simanek, 2004). An example of this includes Stephan and Stephan (2017), who made use of such a technique to illustrate the amount of uncertainty in their life cycle water, energy and cost analysis results based on each sensitivity parameter tested.

Other graphical methods used include box plots, which illustrates the distribution of the data based on minimum, first quartile median, third quartile and maximum. However, the disadvantage of a box plot is that the exact values and details of the distribution of the results are not retained and they only provides a simple summary of the distribution of results (Ladkin, 2017). Another method similar to box plots are violin plots except that they show the probability density of the data at different values and used to represent comparison of a variable distribution. Violin plots typically illustrate more information than box plots, however are not as popular and thus potentially harder to understand and interpret due to lack of familiarity with their representation (The Data Visualisation Catalogue, 2017; Hintze and Nelson, 1998). Another method is the tornado diagram, which is used for deterministic sensitivity analysis in comparing the relative importance of variables. The length of the bar indicates how sensitive the output is to each variable. This technique is quite useful in illustrating a potential range of results (a low and high range). However, the tornado diagram only shows the total impact (Eschenbach, 1992).

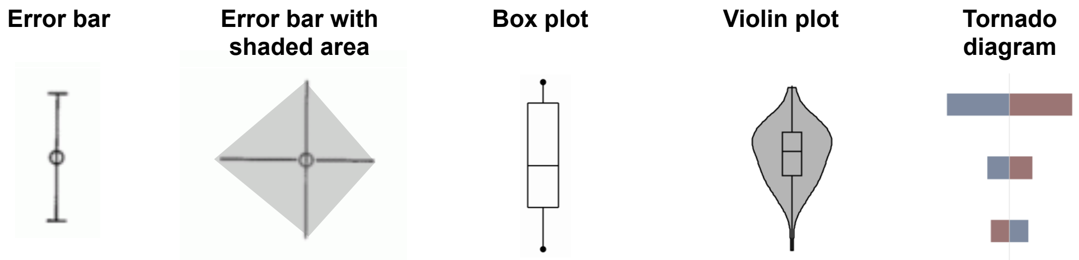


Figure 2.6 Example of methods available to illustrate uncertainty graphically

2.3.7. Summary

LCA provides a useful tool for analysing and evaluating a project on a holistic level as all life cycle stages are considered and form part of the decision-making process. The consideration of more than one life cycle stage, as is so often done within industry and research, can result in a greater understanding of the project's environmental impact can be achieved.

Comparative LCA provides a useful mechanism to compare and evaluate the project options available so that the most suitable option is selected. A streamlined LCA further narrows the focus of the analysis so that only the energy or only the GHGE, dependant on goal of study, can be focused on so as to achieve further refinement. Examples of both LCEA and LCGHGE are provided in the section above. These studies demonstrate what kind of data can be extracted from the results, such as comparing the embodied emissions to the operational impact, or of the embodied impact to the overall life cycle impact.

The use of data collection methods, such as IO or Hybrid, will further compliment the holistic approach so that the maximum possible upstream process, so often neglected from LCA studies, can be included in the calculations.

Due to the subjective nature of the LCA approach, attention should be paid to the various steps involved with the methodology and the assumptions and decisions inherent in each step. There is a need to clarify issues such as objectives, methodology, terminology, geographic location and age of data, to ensure that greater transparency is achieved (Menzies et al., 2007). The greater the level of transparency, reduces the possible extent of misinterpretation of results. Sensitivity analysis will further compliment this quest for transparency and highlight key variables that significantly affect the results, and identify areas that might require further investigation.

A conventional LCA does not consider the social or economic aspects of a product or building (Crawford, 2011; Gu et al., 2008). Decisions within the construction industry are often based on economic matters, with the cost of the buildings and its components acting as the main proxy for investment decisions. LCA provides the user a means to base decisions on the expected environmental impact, however understanding the expected economic impact of these decisions will enhance understanding of the project at hand. Zuo et al. (2017) have stated that LCA is in a state of transformation as can in fact be renamed as 'life cycle sustainability assessment' as LCA is starting to include several other aspects such as social and financial sectors. A method that compliments this life cycle approach, but through financial terms, is called LCC analysis, which is discussed in more detail in the next section.

2.4. Quantifying life cycle cost of buildings

Building design decisions are usually based on issues pertaining to construction cost (Langston and Langston, 2008) with capital cost remaining as the primary criterion for building procurement decisions. Financial costs play a major role, particularly when it comes to low carbon (sustainable) construction with the consideration of 'green' design is always prefaced with the question 'How much more will this cost?" (Jackson, 2008). Cost can often be an alienating factor when it comes to low carbon buildings (de Blas, 2012) due to the public perception that 'green' design is expensive. A crucial issue for both owners and occupiers is 'cost-effectiveness' of low carbon solutions (Ellis, 2009). The financial benefit, in studies such as Collins et al (2008), has also been linked with more sustainable building design. Their study states that a sustainable building's LCC benefit has been coupled with an increase staff efficiency (which is considerable seeing as staff costs make up 85% of the total costs of a building over its lifetime. However, as mentioned by Collins et al, is that the lack of available objective data makes it hard to quantify. Financial justification is required to help increase its uptake (Warren-Myers, 2012). Several efforts have been made to quantify the economic cost implications of 'sustainable' design in buildings, as described below.

2.4.1. Different life cycle stage perspectives

2.4.1.1. Operational cost perspective

As discussed earlier sustainability-rating tools such as BREEAM, LEED and Green Star, is often used as a benchmark in the determination of the GHGE of buildings from an operational perspective. The capital cost increase of the use of these tools and their relevant ratings have been widely documented in literature. Table 2.3 provides a brief summary of some of the sources and available results.

Table 2.3 Increased capital cost increase from an operational emission perspective

Source	Details	Certification Scheme	Level of certification	Capital Cost increase (%)
Air Quality Sciences (2006)	LEED Assessment	LEED	Undefined	2%
Green Building Council Australia (2013)	31 Green Star buildings in Australia	Green Star, Australia	4 Stars 5 Stars 6 Stars	>10% >5% >15%
Murugan and Kato (2010)	Based on 31 office buildings (also funded by GBCA)	Green Star, Australia	Undefined	10%
Kats (2003)	Based on 33 LEED registered buildings.	LEED	Certified Silver Gold Platinum Average	0.66% 2.11% 1.82% 6.5% 1.84%
Ellis (2009)	LEED assessment	LEED	Basic Level Higher level	2% to 5% 5% to 7.5%

Source	Details	Certification Scheme	Level of certification	Capital Cost increase (%)
BRE (2012)	BRE House, Naturally ventilated office and air conditioned office	BREEAM	Pass Good to Excellent	1% to 3% 7%
Williams (2012)	Dependent on climatic conditions:	Passive House	Germany: Italy: France: Spain: UK:	6.71% 7% 10% 2.85% 5.54%

The results above evidence that the increase in capital cost in pursuing a lower operational emission building varies greatly ranging between 2% to 15% increase depending on what source, certification scheme and the level of certification scheme pursued. Again, these studies do not consider the embodied emissions and focus mainly the economic implications from an operational and capital cost perspective.

2.4.1.2. Embodied (initial) cost perspective

Compared to the operational perspective studies, the financial implication's of embodied emission reduction in buildings has not been as widely analysed. Langston and Langston (2008) state that the correlation between initial embodied energy and capital cost is very strong, however, this value changes from type of material and level of detail analysed. This study further states that an effective strategy of reducing embodied energy is simply building less (which could have an effect on the capital cost) and that spending more initially to save embodied energy is unlikely to be a productive quest. This view is supported by Wu et al. (2015) who state that a low embodied energy house may result in a low capital cost for the owner but the importance of REE must not be underestimated with durability of materials being a potential critical issue. In contrast to these findings, studies such as Imbabi 2012 have found that lower embodied emission materials are more expensive. It is thus important to get the balance right.

In the publication, Redefining Zero (2010), Roberts and Sturgis state that from a purely financial point of view, reducing the embodied emissions through design can be more effective that reducing the operational emissions and that failure to take embodied carbon costs into account can lead to over-specification and wasteful use of both carbon and financial resources (Sturgis and Roberts, 2010).

Wu et al (2015) state that in comparison to operational emissions, it is more difficult to estimate and measure the market value of embodied energy and that emphasis will have to be placed on long-term investment, whereas the current emphasis is on short-term investment.

The Embodied Carbon Task Force in the UK (2014) further emphasises the fact that embodied carbon can be used as a proxy for cost management (ASBP, 2014).

Although these publications, which are few in number, comment on the potential relationship between embodied performance and financial cost in buildings, the economic value of reducing the embodied emissions in buildings remains to be determined. Wu et al's comment above about the importance of durable materials and thus resultant consequences on REE serves as a reminder that in the quest to determine this economic value, the other life cycle stage such as recurrent and operational, should not be ignored. Though it is alluded that embodied emission reduction may lead to a reduction in capital cost, the consequential effect on operational costs and maintenance costs must be accounted for. This leads to the next section that introduces the concept of examining the economic consequences from a life cycle perspective (thus including embodied and operational).

2.4.1.3. Life cycle cost perspective

Capital cost, either for the building itself or capital cost associated building additions such as energy efficient equipment, is often used as a main proxy for investment decisions. However these initial costs have been estimated to only represent only 50% of the life cycle cost (over a buildings useful life of 40 years) (Flanagan et al., 1989). Although these percentage estimates vary widely across studies (Mithraratne et al., 2007), the long life span of buildings needs to be taken into account. Buildings need to continue to provide their services over other life cycle phases of the building, as illustrated in the Figure 2.7 below. These phases can include running costs (including operating and maintenance costs) and end of life costs (which include recycling and demolition costs).

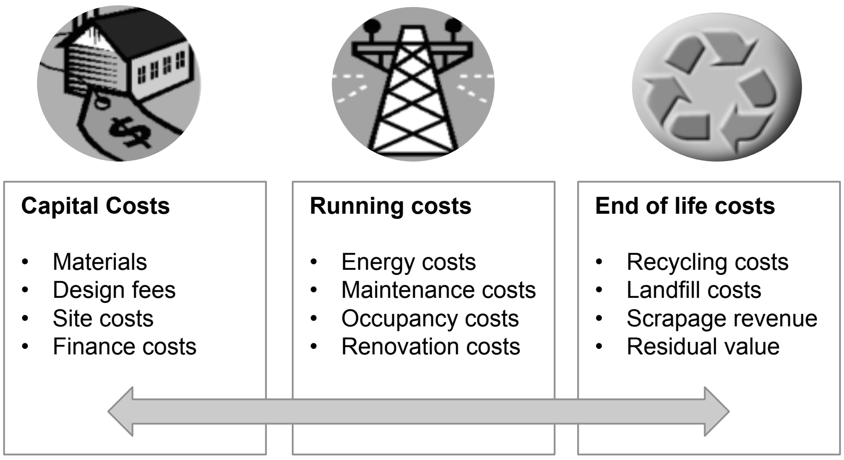


Figure 2.7 Total cost of building ownership

Source: Menzies (2010)

LCC provides a method for the assessment of the costs incurred over the various life cycle phases of a building and provides a useful tool in comparing building design options. LCC is widely acknowledged as one of the several methods that can be used to account and provide for a more comprehensive view of building related costs (Goh and Sun, 2015). The following section describes LCC assessment in greater detail, together with key terms and concepts, calculation methods and other considerations.

2.4.2. Life cycle cost analysis

LCC Analysis is defined as a 'technique which enables comparative cost assessments to be made over a specified period of time, taking into account all relevant economic factors, both in terms of initial costs and future operational costs' (Standardized Method of Life Cycle Costing for Construction Procurement ISO 15686 2008). Cabeza et al. (2014) provide another LCC definition by describing it as 'the total discounted dollar cost of owning, operating, maintaining and disposing of a building or a building system'. LCC can help determine trade-offs between the options considered and help determine how long it will take for a specific system to 'pay back' its incremental cost. LCC can be used for an entire building or for individual building elements.

Traditional LCC is purely economical and does not take environmental aspects into account, but continuing development on the field has developed the LCC model to calculate other factors such as total energy costs and environmental considerations, such as GHGE, in buildings (Ristimäki et al., 2013; Schwartz et al., 2016). The primary use is in the evaluation of alternative solutions to specific problems (Ashworth and Perera, 2015).

Similar to LCA, there are a series of steps that must be followed in order to complete a LCC, as illustrated in Figure 2.8 below. The first step is to define alternative strategies to be evaluated. The next step is to identify the economic criteria (such as discount rate and analysis period). The third step is to obtain and group significant costs. The last step is to perform a risk assessment, also referred to as a sensitivity analysis.

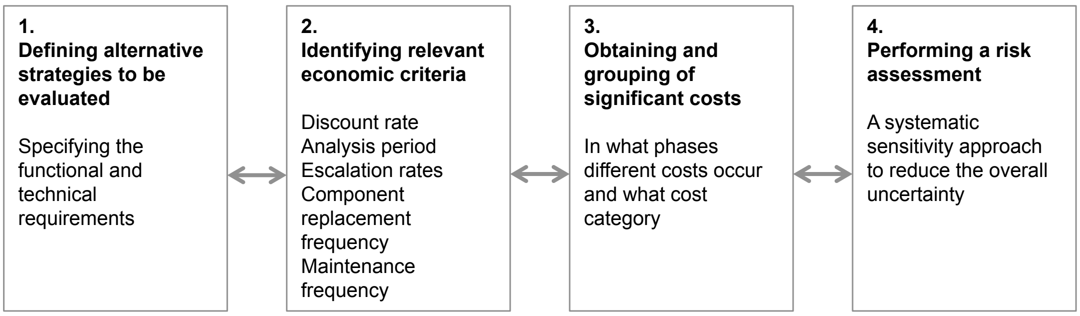


Figure 2.8 LCC Approach

Source: ISO 15686 2008

There are several key concepts to consider when evaluating the financial cost of buildings, especially over the life cycle of a building, as explained in the following section.

2.4.2.1. Key terms and concepts

Time value of money

The 'time value of money' is a term used to describe the difference in value between money today and money in the future (Berk and De Marzo, 2014). In other words, the present capital is more valuable than a similar amount of money received in the future (Boussabaine and Kirkham, 2004). Factors such as inflation, interest rates and discounting process affect the value of money today (present value) versus money in the future (future value).

Interest Rate

Interest rate reflects the rate at which money today can be exchanged for money in the future. For example, \$1 today with an interest rate of 7% will accumulate to the value of \$1,07 in one year's time. The 7% quoted before reflects the '*risk-free interest rate'*, *r*, for a given period. The interest rate is based on two components: the time value of money and inflation (Geltner et al., 2007). For cost calculations, the 'interest rate factor, *(1+r),* is used to represent the dollar exchanged today for the dollar in the future, i.e. "$ in one year/$ today". Two other terms to be aware of is 'compound interest' which is the process of earning interest on interest (i.e. (*Money today $) x (1+r) x (1+r) x…)* and 'simple interest' is the interest earned in one year without the effect of compounding.

Inflation

Inflation, in economics terms, describes the gradual loss of purchasing power in the dollar as prices of the same goods and services rise over time. Interest rates are either quoted in terms of 'nominal interest rates' (which excludes inflation) or 'real interest rates' (which has been adjusted for inflation to reflect the actual purchasing power return net of inflation). Unless it is specifically stated otherwise, interest rates are most often quoted in nominal terms (Geltner et al., 2007).

Discounting

A process called 'discounting' is applied to calculate the amount today that a sum of money in the future is worth, using what is termed a specified 'discount rate' (Boussabaine and Kirkham, 2004). A discount rate (DR) depends on inflation, cost of capital, alternative investment options and investment return, exchange rates and can be thought of as an investment premium over and above inflation (Berk and De Marzo, 2014; Islam et al., 2015b; Mithraratne et al., 2007).

The DR used will depend on whether nominal or real costs were being discounted. The nominal discount rate will include a component for inflation while the real discount rate will not include a component for inflation. Since LCC is a comparative analysis exercise, inflation can be omitted (Mithraratne et al., 2007). Refer to Langston (2005) for an example of inflation-free discount rate approach.

The DR forms a vital component of the financial quantification process and significantly affects the interpretation of costing study results. A too high discount rate will bias decisions in favour of short-term capital cost options, while a too low discount factor will give undue bias to future cost savings (Flanagan et al., 1989). There is a range of DR used across costing studies in buildings, but the most accurate discount factor should reflect the particular circumstances of the project, the client and prevailing market conditions (Ashworth and Perera, 2015). For example, a DR used for a study in Lebanon cannot be accurately compared against a Melbourne based study. The DR selected will also depend on the type of investor. If it is a private investor, the bank rate will probably be used as the return on investment. A business investment would expect a higher return and a public investment usually a lower return (Mithraratne et al., 2007).

Table 2.4 briefly demonstrates the varied range of discount rates found in previous costing studies.

Table 2.4 Discount rate values in previous consulted studies

Author and date	Discount Rate %	Notes
Stephan and Stephan (2016)	12.2%	High discount rate due to the investment risk in Lebanon compared to other developed countries
Morrissey and Horne (2011)	3.5% applied for the first 30 years of analysis 3% for the 30-75 years period	Completed over 50 years for their study in Melbourne Australia.
Leckner and Zmeureanu (2011)	4%	Study on net zero energy house in Montreal, Canada
Kneifel (2010)	3%	USA based study.
Bull et al. (2014)	3.5% from year 0 to year 30 3% from year 31 to year 60	UK based study.
Kats (2003)	5%	USA based study for validating the implementation or 'green building design' in California
Mithraratne and Vale (2004)	Australia: 5 – 9% International: 3-4%	Based on the Standards New Zealand these are the real discount rates the Australian government uses.

Present Value and Future Value

Present value (PV) is the term used to express the present day value of dollars. It is the present exchange value of that future sum given the interest rate at which it is calculated (Flanagan et al., 1989). The same calculation can be reversed to 'move cash forward' for the calculation of the Future Value (FV). The above process can be summarised with the following graphic adapted from Berk and De Marzo (2014), as illustrated in Figure 2.9 below. Which illustrates that in order to move cash flow forward on must compound it. To move cash flow backward, one must discount it.

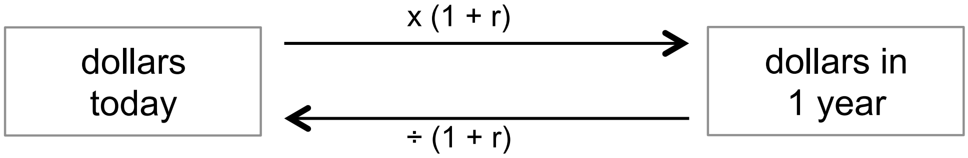


Figure 2.9 Converting between dollars today and dollars tomorrow

Source: Berk and De Marzo, 2014

Refer to (Berk and De Marzo, 2014) for a more detailed example of the PV and FV calculation process.

Period of analysis

The study period is another vital aspect of costing studies. Building lifespan assumptions vary quite significantly across a range of LCC studies due to the fact that there is little consensus on the lifespan of buildings and their elements/ components (Islam et al., 2015a; Ashworth and Perera, 2015). Buildings have varied patterns on existence and, deterioration and obsolescence commence as soon as they are erected (Ashworth and Perera, 2015). Longer study periods are often more effective at capturing the relevant costs across a range of life cycle phases on a building. However the longer the study period, the greater the amount of uncertainty as future events becomes harder to predict (Kneifel, 2010). For example events relating to building component life include uncertainty regarding future maintenance costs, maintenance policies, hidden costs and non-identical replacements.

There are a few other aspects to consider of when interpreting cost studies and their subsequent study period. One such factor is that different study periods will represent different interests to different stakeholders. The initial period, for example, might be more related to the developer whereas the operational period to the building occupier (Kneifel, 2010). Another critique to be aware of is that the discounting process can render future costs and benefits insignificant when a lengthy time horizon is involved (Langston, 2005). Examples of the variety of study periods used in cost studies are included in the Table 2.5 below.

Table 2.5 Examples of period of analysis

Author	Period of analysis	Notes
Stephan and Stephan (2016)	50 years	Lebanon based study for a residential building.
Kneifel (2010)	10, 25 and 40 years	USA based study for commercial buildings that used different study periods so as to represent various stakeholders possible interest period.
Leckner and Zmeureanu (2011)	40 years	Canada based study for net zero energy house.
Bull et al. (2014)	60 years	UK based study for a school.
Kats (2003)	20 years	California based study on LEED buildings and their LCC cost.

2.4.2.2. Methods available for life cycle analysis

Discounted cash flow analysis

Discounted cash flow (DCF) analysis is a technique for “assessing the return on capital employed in an investment project over its economic life, with a view to prioritising alternative courses of action that exceed established profitability thresholds”(Langston, 2005). It is based on the fact that investment projects typically span over more than 1 year and therefore involve future costs and benefits. DCF is used to assist decision-making and accordingly is ordinarily used as a comparative technique (Robinson, 1989). It allows for costs arising at different time scales to be compared and encompasses the time value of money and other concepts described in the previous section. It is based on the concept of cash inflows and cash outflows. Cash inflows relate to the benefits received from a particular project while the cash outflows are the expenses arising during the course of the project. The net cash flow is the difference between the cash inflows and outflows. Langston (2005) states that “projects that exhibit cash inflows (benefits) earlier in their life are preferable to investments where cash inflows are delayed. Similarly, investments that exhibit cash outflows (cost) later in their life are preferable to investments where cash outflows are accelerated”. This can also be referred to as ‘personal rate of time preference’ (i.e. people prefer revenue sooner rather than later). There are two basic DCF methodologies, ‘Net Present Value’ and ‘Internal rate of return’, as described in the following section.

Net present value

A common analysis method for LCC is the Net present value (NPV) approach (Zuo et al., 2017), which is the sum of the discounted present values of all future cash inflows and outflows. If the NPV is positive, the project will produce a profit. If the NPV is negative, the project will come at a loss. If the NPV is zero, one will neither gain nor lose by accepting the project. Berk and De Marzo (2014) state that the NPV decision rule can be used when comparing options, by selecting the project with the highest NPV. A tactic that is often useful is to compute the NPV profile, which is a graph of the projects NPV over the range of discount rates. The basic calculation procedure used for NPV is to divide the cash flow for a certain period by the discount rate totalled for the number of years (refer to Berk and De Marzo (2014) for a more detailed description and calculation procedure).

There have been several energy related studies that have used the NPV approach to estimate the financial benefits in relation to energy savings. Morrissey and Horne (2011), is a Melbourne based study where the NPV was compared for different energy efficient measures in new residential projects. Another example is Stephan and Stephan (2016) who looked at the LCE and LCC of various energy reduction measures for a residential building in Lebanon. Schwartz et al. (2016) used NPV to assess the LCC for a council house refurbishment in England. Other examples include Bull et al. (2014), Kneifel (2010) and Islam et al. (2015b). NPV is often quoted as "the most accurate and reliable decision rule" when selecting and assessing projects (Berk and De Marzo, 2014; Langston, 2005). However Flanagan et al. (1989) highlights some issues to consider of when calculating the NPV of projects:

- Timescale: expected life of building or component vs. the period of analysis (these two timescales will not necessarily be the same)
- Obsolescence and deterioration: Obsolescence (value decline that is not caused directly by use or passage of time)
- Depreciation: Economic consequence of deterioration
- Salvage and residual values
- Double counting: Some costs counted twice

Internal rate of return

The Internal rate of return (IRR) is the DR that, if selected, will lead to a NPV of zero. In other words where the value of the future income stream is equal to the initial cash outflow. The IRR rule, as quoted from by Berk and De Marzo (2014), stipulates that "take any investment opportunity where the IRR exceeds the opportunity cost of capital. Turn down any opportunity who's IRR is less than the opportunity cost of capital". It is a classical and traditional measure of investment and can be 'easily calculated' (in comparison with NPV) (Geltner et al., 2007) and is commonly established by iteration or trial and error or the use of formulas present in software programs such as Microsoft Excel. The main aim of using the IRR technique is to reflect on the relative productiveness of the capital being committed to the project under investigation, not to provide an absolute measure of profitability (Langston, 2005).

There are some issues to be aware of when using the IRR method. The IRR method can result in misinterpretation for projects with delayed investments (when for example a project incurs cash upfront but costs at a later stage), multiple IRR's (some projects can have an outcome of multiple IRR values where the only choice is then to use the NPV method instead) or non-existent IRR (no discount rates that make the NPV equal to zero). According to Berk and De Marzo, relying on the IRR in isolation to make investment decisions "can be hazardous"(2014). However, the IRR can be a useful method when employed along the with NPV method. It can provide useful information regarding the sensitivity of the projects NPV to errors in the estimate of its cost of capital (Berk and De Marzo, 2014). An example of a study that included both the NPV and IRR method is Kneifel (2010). The NPV technique was used in conjunction with the adjusted IRR (which is the annualised return on the energy investment costs) and then compared with the investors' minimum acceptable rate of return (MARR).

The IRR is also easy to compute, as the capital value of the investment at intermediate points in time is not needed for the calculation. Another reason why IRR is used is that it is a dollar weighted average return (i.e. it includes only the returns earned on capital while it is invested in the project), in contrast to a time-weighted average (Geltner et al., 2007).

Payback analysis

The payback analysis is sometimes used as an alternative to NPV or the IRR method discussed above. This method stipulates that a project will only be selected if its cash flows pay back in its initial investment within a specified period (Berk and De Marzo, 2014). A term often used is 'payback period' which refers to the amount of time it will take a project will take to pay back the initial investment. There are two methods, either 'discounted payback method' (time value of money considered) or 'simple payback method'. Though the payback method is easy and quick to preform it is not suitable for LCC studies (Mithraratne et al., 2007). It ignores the projects cost of capital; ignores cash flows after the payback period and may not factor in elements such as compound interest and discounting (Berk and De Marzo, 2014). Leckner and Zmeureanu (2011) further emphasise that the 'simple payback method' does not necessarily include effective interest rate or rising energy prices of replacement cost, potentially leading to inaccurate investment decisions. Jackson (2008) further confirms that this method is not really suitable for studies that deal with energy efficient investments, as it is too rigid and does not have enough flexibility to be suitable for these types of studies.

2.4.2.3. Limitations to life cycle cost analysis

One aspect that continues to plague LCC studies is the collection of accurate cost data. Manufacturers and developers often keep cost proprietary and there is a limited amount of 'real' cost data available (Kats, 2003). Building related LCC's also require the assessor to estimate future energy costs, which is quite complicated due to rapidly changing tariff structures and uncertainty towards future events. This lack of data then results in the use of various assumptions in order to predict the cost of materials and resources, which contribute to the overall uncertainty of the costing study result.

The boundary of the study (i.e. what costs are included or excluded) and the methodology need to be transparent in order to avoid misinterpretation of the results. Other barriers affecting LCC studies, as defined by Mithraratne et al. (2007) and Langston (2005), are the lack of accurate cost data, the need for multiple assumptions, lack of industry standards, lack of appropriate application due to limited industry knowledge and expertise, inconsistency to discounting process and application in later design stages (when it is more difficult to modify the design).

2.4.2.4. Dealing with uncertainties in life cycle cost assessment

Forecasting and assumptions form an integral part of life cycle studies. LCC studies in particular, include a significant level of uncertainty as the future is being forecast on the basis of current data and knowledge (Flanagan et al., 1989; Islam et al., 2015a). As Langston states "forecasting models are abstractions from reality". It is impossible to know what the price of goods will be in the future and what other factors may affect the price, such as technological advances. The term 'risk' refers to the possibility of the investor not receiving the expected or required rate if return from the capital invested (Robinson, 1989). These risks can also be classified into macro risks, such as the economy, interest rates, inflation, labour unrest, lifestyle changes, obsolescence, legislation and taxation. Project specific risks which include development risks (such as construction costs); investment risk (tenant or lease issues) and financial risks (such as business cycle or market sector). The term 'uncertainty' is often coupled with these 'risks' and refers to the state of knowledge about the variable inputs to an economic analysis.

According to Langston (2005) there are two approaches available for risk analyses, namely deterministic or probabilistic approach, as briefly described earlier Deterministic approaches include conservative benefit and cost estimating, break-even analysis, sensitivity analysis, risk-adjusted discount rates and certainty equivalent techniques. Probabilistic approaches include input estimation using expected values, mean-variance criterion and other mathematical techniques. A probabilistic approach is often viewed as more complex to execute, with the deterministic approaches being favoured for analysing uncertainty. Sensitivity analysis in particular is the most common technique used in LCC studies.

For cost calculations such as NPV, Flanagan et al (1989) recommend a sensitivity analysis. This is where the NPV calculation is broken down into its components and demonstrates how the NPV varies as the underlying assumptions change (Berk and De Marzo, 2014). By breaking down the components, it identifies the assumptions, from the discount rate or study period for example, that alter the results most significantly. As explained above, variables like DR and period of analysis can significantly influence the results. For example, a too high DR will bias decisions in favour of short-term capital cost options, while a too low DR will give undue bias to future cost savings (Flanagan et al., 1989). High DR often results in a project being selected with low-capital-cost high-operating-cost alternatives (Langston, 2005). Another major source of error is prediction of the future costs and the frequency of maintenance and replacement (Mithraratne et al., 2007).

When risk analysis is required for a project where more than one variable or parameter may affect the outcome, a technique known as scenario analyses can be implemented. Specific scenarios are identified, such as a high cost or low cost scenario for example, and applied to the project in order to understand how multiple project parameters may affect the outcome. Table 2.6 summarises some of the suggested variables to be included in sensitivity analysis regarding costs studies:

Table 2.6 Factors to be included in a LCC sensitivity analysis

Author and date	Factor to be included in sensitivity analysis
Stephan and Stephan (2016)	Different inflation rates with discount rate Assume energy inflation will not be similar to general inflation rate
Morrissey and Horne (2011)	High and low energy costs
Leckner and Zmeureanu (2011)	Different discount rates Different inflation rates Different period of analysis
Islam et al. (2015b)	Different discount rates Commercial nature of prices
Flanagan et al. (1989)	Period of analysis Different discount rate (the higher the discount rate chosen, the less the weight attached to the future costs included in the calculation and the greater the weight attached to initial capital costs) Life expectancy of the options Various cost estimates Rate of inflation
Langston (2005)	Range of discount rates
Mithraratne et al. (2007)	Period of analysis Discount rate Life expectancy of the material/ element Estimated cost Rate of inflation
Ristimäki et al. (2013)	Indexation Discount parameters

2.4.3. Summary

LCC provides a mechanism for the comparison and evaluation of different building design options based on total life cycle cost. This includes the initial construction costs, operating and eventually the end of life costs, therefore providing a more holistic picture of what the economic implications would be for the user. There are several life cycle phases and corresponding cost phases to consider, and the system boundary of the cost study must clearly state what has been included or not.

LCC is based on the concept of the time value of money, where money today will not have the same value as money in the future. In order to take into account that future costs are lower in value, an appropriate DR has to be applied to all the expenses arising in different points in time to convert it to present value. The DR forms a vital part of cost calculations and can have a considerable impact on the results. A DR that is appropriate to the context and purpose of the study must be selected.

DCF analysis provides a technique to incorporate the effect of discounting on future cash inflows and outflows. There are two principal methods available for this analysis are NPV and IRR. NPV is the sum of the discounted present values of all future cash inflows. The NPV approach is often quoted as the 'most accurate and reliable decision rule' and provides an effective way to compare and evaluate projects. IRR is the DR, if selected, will lead to a NPV of zero. The IRR, when used in conjunction with the NPV method, can help highlight the sensitivity of the NPV to estimate error in the cost of capital.

Other methods available, such as the payback method, are not suited to LCC studies, as the costs beyond the period of payback are not considered.

A significant number of assumptions is inherent in LCC studies, as the future is uncertain and it is impossible to know the exact future costs of goods, future economic events or advances in technology and uptake, for example. Thus it is paramount to any cost study to clearly state what the assumptions are so as to avoid misinterpretation of results. In order to deal with this uncertainty, a sensitivity analysis can be preformed to identify the key variables that may alter the results most significantly.

There are still several barriers affecting the uptake of LCC studies within the construction industry. Cost studies are predominantly focussed on either initial/ capital costs or operating costs. Key emphasis is placed on decreasing initial construction costs instead of decreasing life cycle costs. A holistic approach, incorporating as many life cycle stages as possible, must be assumed so as to provide more comprehensive results. Other factors, including the lack of data and lack of industry standards, for example, also plague the LCC process.

As the growing awareness of climate change continues to evolve, the need to gain a better understanding of how a building preforms over its life cycle, from a GHG, energy and cost perspective. Demonstrating how resources (economic and environmental) can be used more effectively to deal with current and future challenges is paramount. Methods such as LCA and LCC will provide vital keys for this challenge.

The following section will introduce the present state of knowledge regarding combining LCA and LCC for building evaluation.

2.5. Integrating life cycle analysis and life cycle cost assessment

LCA and LCC have predominantly been used in isolation of each other, but there has been an increasing number of academic studies and commercial tools that have started to combine both these forms of assessment in their analysis of the building performance. The combined use of LCA and LCC can deliver true long-term value for a client (Goh and Sun, 2015), with studies such as (Gluch and Baumann, 2004), suggesting that there is a need for economic evaluations must have environmental dimensions.

The first section describes the previous academic studies that have used both LCA (either LCEA or LCGHGE) and LCC to either suggest a new framework, tool or method. The second section provides a brief overview of the commercial software tools currently available that currently provide both these forms of assessments. This section concludes with the key weaknesses and gaps that must be addressed in order to evolve the LCA and LCC integration process.

2.5.1. Previous studies

Previous studies that include both LCA (either LCEA or/and LCGHGE) and LCC can be broadly classified in two groups. The first group have used the methods and data already inherent in LCA and LCC in order to provide a building or product evaluation, and is discussed first below. These evaluations tend to conduct either an LCA first to be followed by an LCC analysis and include examples such as Leckner and Zmeureanu (2011), Ristimäki et al. (2013), Bull et al. (2014) and Schwartz et al. (2016). In contract to this, the second group sets out to integrate LCA and LCC either in the form of a new method (Gu et al., 2008), framework (Deng et al., 2008; Heijungs et al., 2013), model (Bierer et al., 2015; Ding, 2005; Hamdy et al., 2013; Savino et al., 2017) or tool (Anastaselos et al., 2009; Hoogmartens et al., 2014; Petrillo et al., 2016). An overview of the studies consulted is provided in Appendix A Table A1 and describes the strengths and weakness of each study along with details of the LCA and LCC inclusions. Some key aspects relating to these studies are discussed below.

2.5.1.1. Studies that utilise LCA and LCC separately

Studies that include both LCA and LCC as part of a building assessment often use the terminology, data sets and calculation methods already inherent in each approach. The calculations and analysis are often performed separately first as the initial part of the assessment. The second part of the assessment then compares and evaluates the results of the LCA and LCC. These studies are more concerned with analysing the relationship between LCA and LCC and indicating how these two entities can be evaluated concurrently in order to aid the decision-making process and have been discussed in (Fouche and Crawford, 2017).

A study that demonstrates how the LCA and LCC framework can initially be used separately at first, and the results thereafter integrated in order to provide an assessment based on both cost and environmental performance is the Finnish study completed by Ristimäki et al. (2013) of a new residential district energy system (which includes seven residences). LCC data was collected and calculated manually based on the NPV methodology over a 25-year period (a 50 and 100 year period was also included to test the sensitivity). The life cycle affordability of each option was calculated by including the replacement, maintenance, energy and investment cost. This was followed by a streamlined LCA assessment, which was calculated with the aid of an input-output-based software model ENVIMAT (which is based on the input-output matrices of the Finnish economy) to help estimate GHGE of construction activities. For their inventory analysis a tiered hybrid approach was used where process analysis for the emissions of production processes is used along with input-output analysis to model the indirect emissions. Their findings are then presented in one graph with net present cost on the left and GHGE on the right, as illustrated in the Figure 2.10 below.

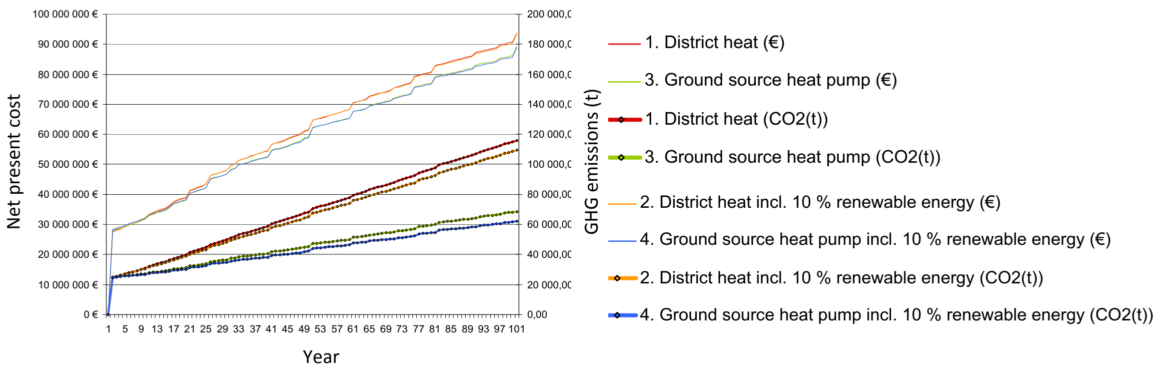


Figure 2.10 Example of the cumulative LCA and LCC outcome over a 100 years for a new residential district heating system

Source: Ristimäki et al. (2013)

This study concluded that by selecting slightly higher investment costs could cut a significant proportion of energy costs and emissions could be cut. They also found that the economical and ecological life cycle outcomes follow similar trends and "clearly support each other from a life cycle perspective". Their study also clearly highlights the impact of uncertainty on the results by stating that "GHG modelling is based on multiple assumptions that have significant effect on the results" and further analyses regarding the sensitivity of these factors will have to be carried out. The specific calculations used are unclear and would aid interpretation of the results. In addition software packages each have their own data sets and internal calculations, which are often unclear to the user.

An example that demonstrates the inclusion of detailed embodied inputs and the development of a supplementary tool to aid assessment is the New Zealand based study by Mithraratne and Vale (2004) where IEE and cost of building materials along with the operating energy and cost of three residential buildings were analysed. A tool developed by the University of Auckland, called the Life Cycle Analysis Model, took both these energy and costs considerations into account and found that the embodied energy was higher in the energy efficient house but operating costs were reduced resulting in a decrease in the overall energy demand. Again the assumptions inherent in the tool have to be clear to aid interpretation of the results.

Another Australasian example is the study completed by Langston and Langston (2008) where 30 buildings (both residential and commercial), located in Melbourne, were analysed and resulted in a strong correlation between capital cost and embodied energy in buildings as illustrated in the Figure 2.11. This is also one of the limited examples of studies consulted that made used hybrid analysis, instead of process analysis alone, for their life cycle inventory. Their study, however, did not include other life cycle phases such as operational costs.

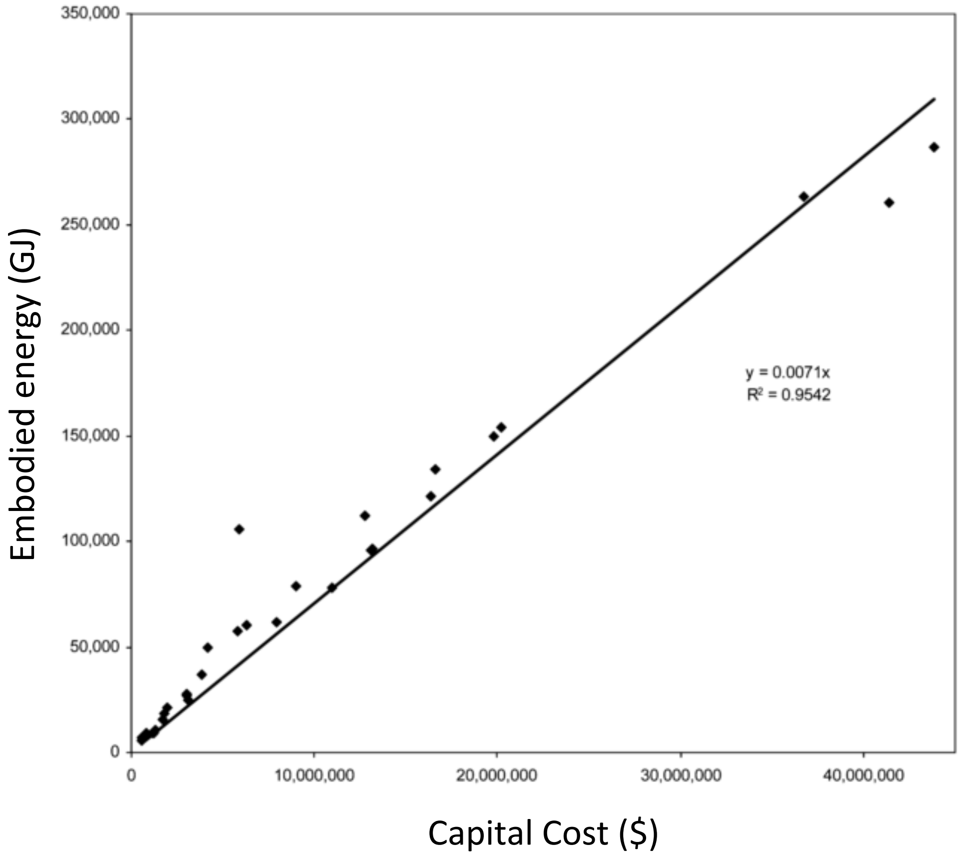


Figure 2.11 Correlation between embodied energy and capital cost based on 30 residential and commercial buildings

Source: Langston and Langston (2008)

Another study that found a "reasonable linear correlation between embodied energy and cost of building components" was completed by Jiao et al. (2012) which looked at two conventional building forms in China and one energy efficient building located in New Zealand. In order to narrow down the scope of their analysis and thus data collection, they included three selection parameters by only selecting materials that contribute a significant mass to the overall building; have a large influence in the final budget and have a high energy intensity. Both studies are limited to only including the embodied energy (with no other life cycle energy phases considered) and only the capital cost (with no reference to other life cycle cost stages). Even though the embodied energy is taken into account, which is so often ignored within building assessments, it is vital to include the other life cycle stages such as operational, so as to ensure that the resource flows within one life cycle stage does not increase flows within another life cycle stage.

Another study that also used an energy efficient building as a proxy for analysis is the LCC and energy analysis conducted for a net zero energy house in Canada by

Leckner (2008). This study included passive measures (such as improving the thermal envelope) and then followed by active measures (such as solar combisystem) in an attempt to reduce the energy demand. This study considered the operating and embodied energy of the house together with the energy payback. The LCA demonstrated a decrease in life cycle energy use but the LCC demonstrated that due to the high cost of solar technologies and low cost of electricity in Montreal the financial payback was never achieved. However process data was used (due to the use Athena software (Institute, 2015)), which can result in an underestimation of the embodied energy, as discussed earlier, which may alter the outcome of the results. Caution should also be exercised when using the payback method, as economic parameters such as the time value of money and discount rate are not included.

Kneifel (2010) also used the NPV technique to look at both the life cycle GHGE and cost of a number of improvement strategies for new commercial buildings across the USA. Their study utilised 12 prototypical buildings that were used as a base line from which to perform roughly 576 simulations, with the use of thermal dynamic software Energy Plus. BEES software was used for the LCC section of the study. LCA and LCC were conducted over four different study periods, namely 1, 10, 25 and 40 years in order to demonstrate the different stakeholder interest over the life span of the building. Their study concluded that energy efficiency technologies, such as insulation, low-e windows and daylight controls, decreased energy use by 20% and often resulted in a negative life cycle cost because of the need for smaller and cheaper HVAC equipment. In addition, the carbon footprint can be reduced by an average of 16%. This study, once again, used process data which may lead to underestimation of environmental flows.

A UK-based residential study completed by Schwartz et al. (2016) split up their study into two sections. They looked at the embodied carbon and cost first and then secondly, they looked at the operational carbon and cost. They kept the calculations separate, looking first at life cycle carbon footprint (LCCf) and then at the life cycle cost (LCC). Once the values were determined, the relationship between the LCCf and LCC values was plotted on a graph (Figure 2.12). With the use of multi-objective genetic algorithms, various building strategies, such as the brick with insulation, illustrated below, were evaluated from both the economic and carbon perspective. Their study found that if a decision were only taken from an energy perspective, a strategy such as large south facing windows would be deemed appropriate. But once the LCCf and LCC were combined, the strategy with (for example) the smallest windows would be selected which would save both cost and carbon over the life cycle of the building. They concluded that even though a selected strategy may save on carbon and financial cost, one also has to consider the user needs (such as the effect that small windows may have on occupant comfort) so as to determine the most 'optimal' solution in the end.

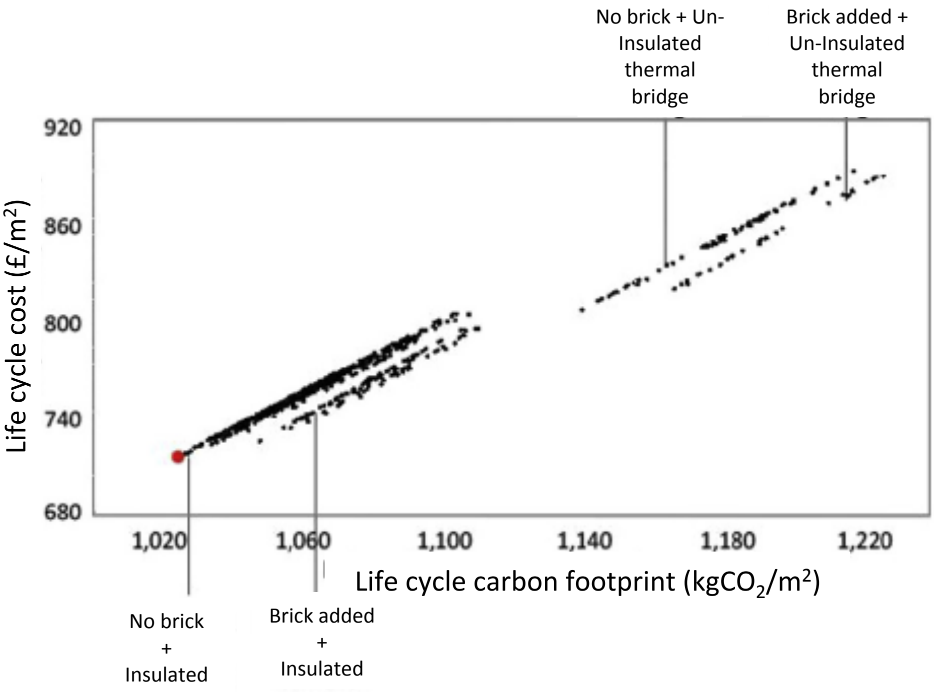


Figure 2.12 Relationship between LCCf and LCC for building refurbishment analyses based on different materials and insulation

Source: Schwartz et al. (2016)

New buildings are often the focus of recent studies but a study that considers refurbishment is that by Bull et al. (2014), where they looked at the energy efficient refurbishment of UK schools and the consequent life cycle effects on cost and carbon. The goal of the study was to establish the retrofit measures and combinations of measures that resulted in the greatest overall reduction of LCCf and LCC. Retrofit measures included insulation (internal and external); improved window glazing; improved air-tightness and more efficient boilers. The life cycle energy was calculated with the use of Energy Plus for operational energy calculations and Bath University data (ICE) (Hammond and Jones, 2011). Costs were estimated from the Cost modelling software. For the LCCf, the operational carbon had a bigger influence than the embodied carbon. Positive NPV values were less common, with only the condensing boiler providing a positive NPV. The worst performing NPV was the internal insulation.

2.5.1.2. Studies that integrate LCA and LCC

The framework diagram provided by the Italian study Petrillo et al. (2016), where the aim was to create a 'tool for the systematic sustainability assessment based on LCA and LCC', demonstrates an example of a possible integrated strategy. They performed their analysis in three different phases, as illustrated in Figure 2.13. Phase 1, 'Analytical', provided the initial analysis and characterisation which included scenario definition and choice of indicators. The second phase, 'Modelling', carried out LCC, LCA and social LCA separately, resulting in a large collection of data. The last phase, 'Assessment', provided a technique to integrate the results from the previous phase thorough methods such as multi-criteria analysis and concluding in ranking assessed options with what they termed as a 'sustainability ranking'. This framework constitutes an example of how LCA and LCC can be performed separately at first (as per Phase 2) and then aim to integrate both results in the last phase of the assessment. This study provides a clear framework but they did not provide a full life energy assessment with the exclusion of recurrent energy (which can represent up to 32% of the initial embodied energy of the building (Treloar et al., 2000b) or provide a clear explanation of the weighting and scaling factors used when creating the sustainability rankings.

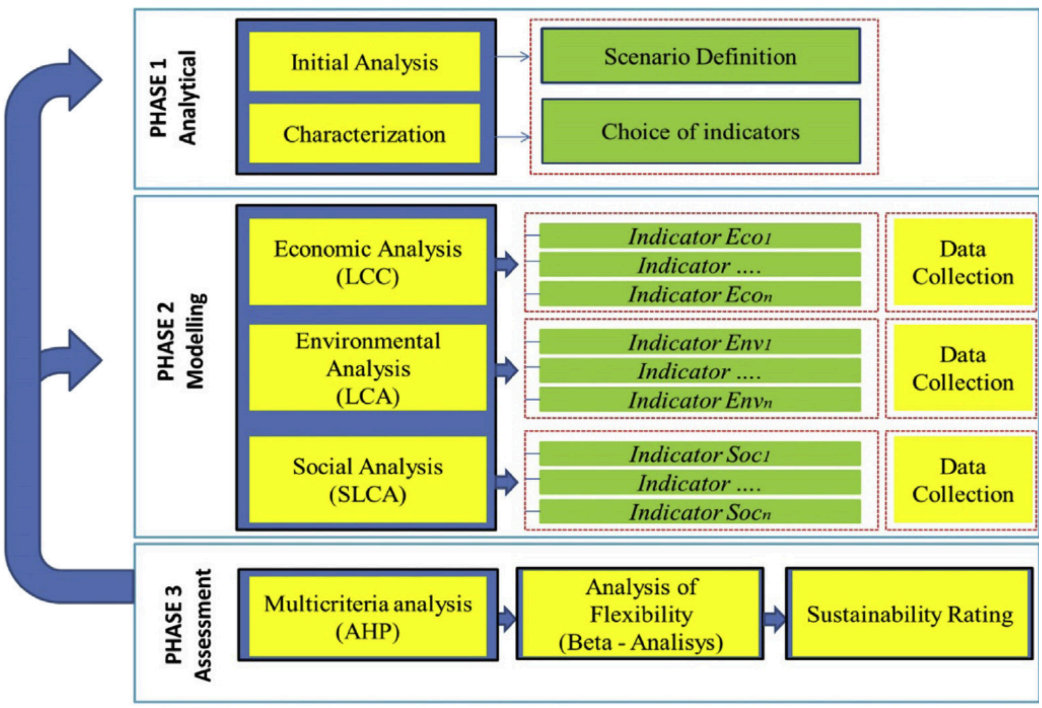


Figure 2.13 Framework for integrating diagram including LCA, LCC and SLCA

Source: Petrillo et al. (2016)

Another example is the Chinese study completed by Deng et al. (2008). Their aim was to develop a framework for the integration of LCA and LCC in order to 'eco-balance' mechanical product design. In the interpretation phase, as illustrated in Figure 2.14, the economic and environmental performance is assessed separately and thereafter integrated to establish the trade-off relationships. Their study resulted in a table that lists the assessed options according to 'improvement degree' and 'integrated benefit matrix'. However, the weighting and scaling factors used to obtain these ranked results are not explained and the lack of graphical output makes it harder for the user to grasp. Other considerations such as the manner in which the 'priority of performance' and 'integrated benefit' were established are not provided.

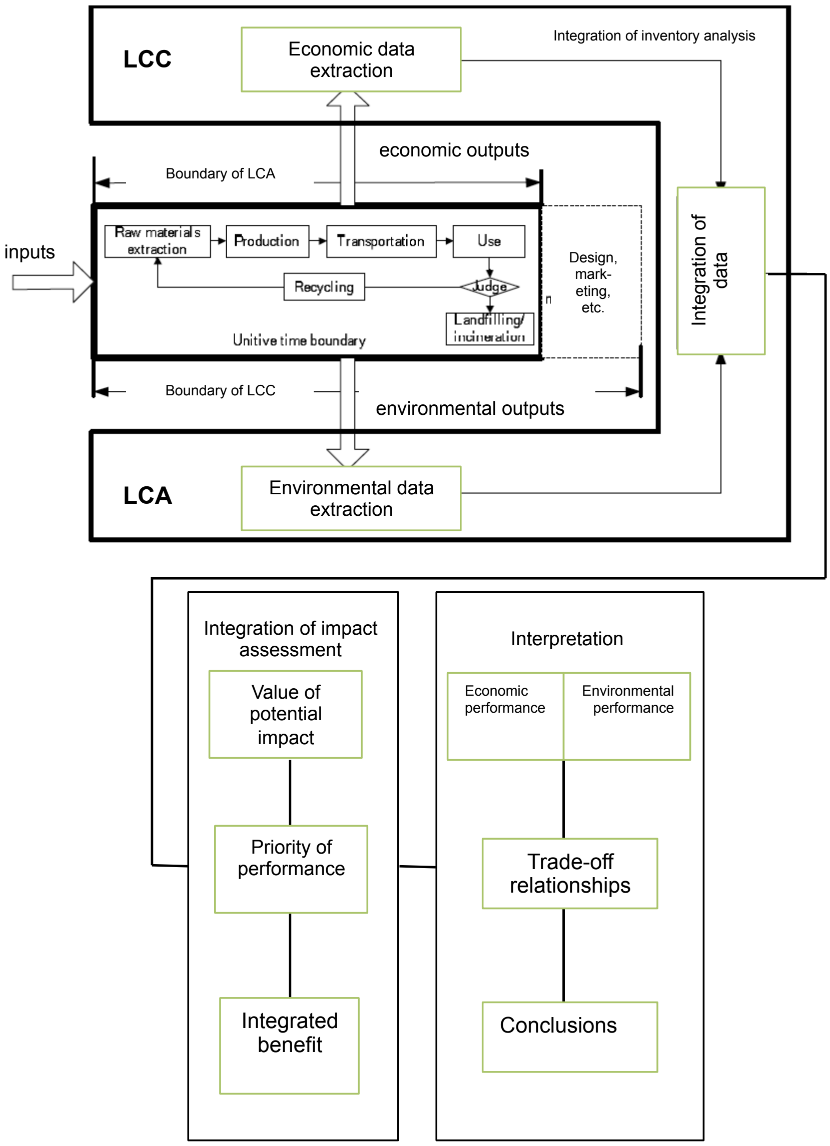


Figure 2.14 Integrated framework example for LCC and LCA

Source: Deng et al. (2008)

A further example is the recent Italian study completed by Savino et al. (2017) that aimed to create a new model for environmental and economic evaluation of renewable energy systems. They created a colour-coded matrix with the GHGE impact on the Y-axis (kgCO_2e), illustrated in Figure 2.15. The matrix is divided in 'optimal region' (which is a low carbon footprint per unit costs) to intolerable region (high carbon footprint per unit costs). Each of the renewable systems was analysed, which in this case all referred to wind turbines, and integrated LCA and LCC results are placed within the matrix allowing the user to clearly see which options are more optimal. However, this study fails to incorporate some allowance for users personal parameters, as what may be optimal to one user might be intolerable to another. Again, the weighting needs to be more transparent especially with regards to how the options were placed on the X-axis and how that came to correspond with the values on the Y-axis.

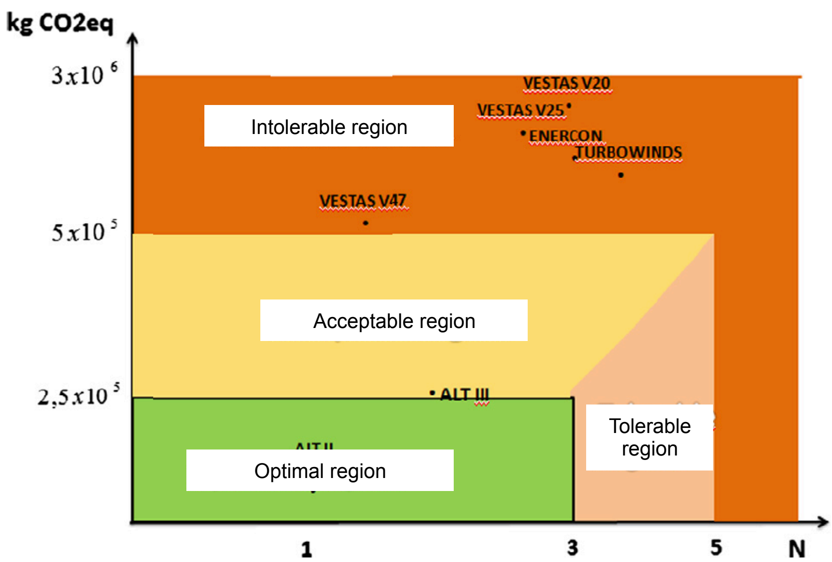


Figure 2.15 Graph illustrating the carbon and cost impact of wind turbine options

Source: Savino et al. (2017)

Another example of a graphical output is found in the Dutch study completed by Huppes and Ishikawa (2005), who aimed to develop a framework for quantified eco-efficiency analysis. Their study places economic value on the Y-axis and both environmental quality and environmental burden on the X-axis, illustrated in Figure 2.16. In the graph the base case is represented by 'H' and the other technologies assessed are labelled 'A' to ' D'. It is quite obvious to see from the graph that a strategy like C comes at a higher economic value but with an improved environmental quality. However, their framework is not applied to a practical building or product example.

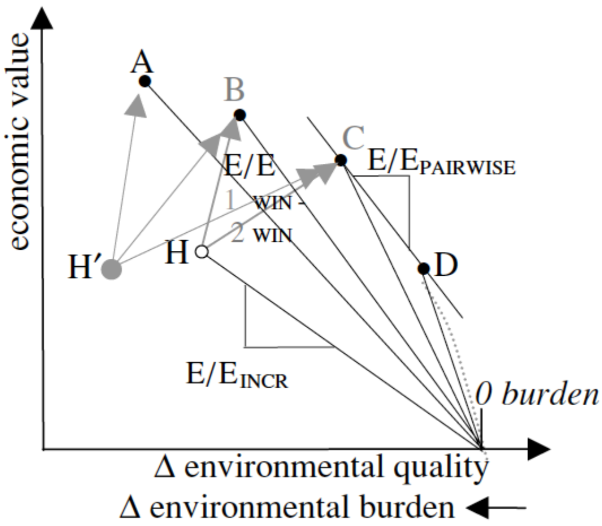


Figure 2.16 Eco-efficiencies of assessed technologies

Source: Huppes and Ishikawa (2005)

Although most of the studies suggest that they are providing a new framework or model, the studies actually make use of the terminology, data sets, methods and calculations already inherent in LCA and LCC analysis respectively. This is clear, for example, from the fact that most of the consulted studies make use of the NPV technique for their LCC analysis and thermal simulation for their operational energy estimations. What these studies instead aim to create is a means of integrating the findings of each form of analysis.

2.5.1.3. Weaknesses and gaps in previous studies

Figure 2.17 below summarises the key weaknesses identified in the consulted environmental and economic studies (please refer to Appendix A Table A1). Table 2.7 (in Section 2.5.3 below) provides an additional summary of these gaps.

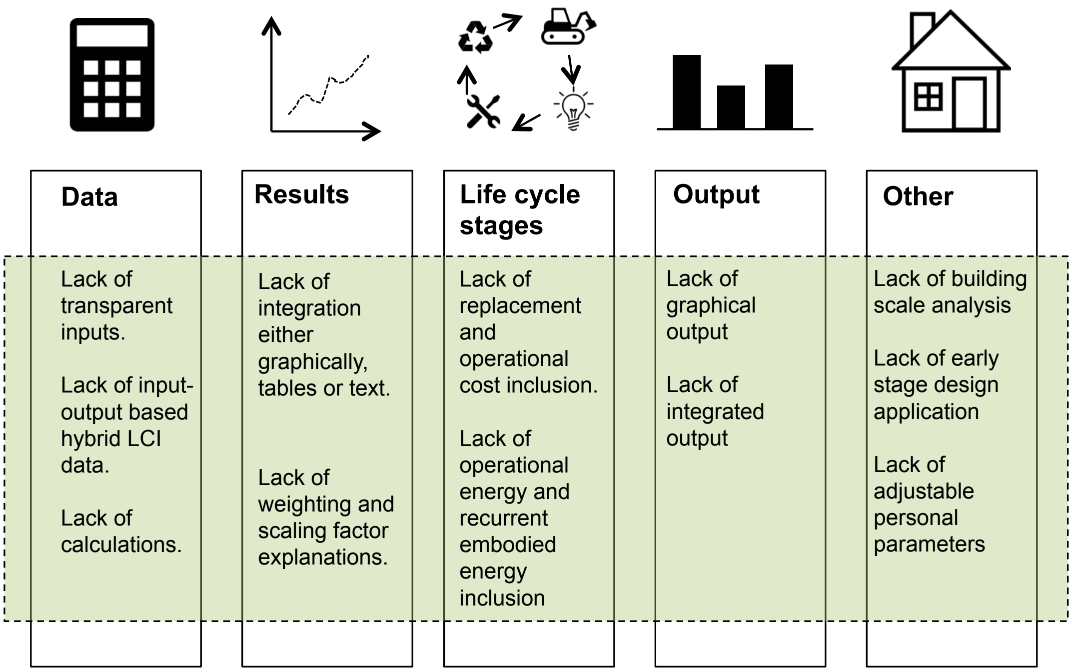


Figure 2.17 Diagram highlighting the key weaknesses of previous environmental and economic studies

The main categories identified were data, results, life cycle stages, output and other. In the data category, there is a severe lack of using input-output based hybrid LCI data in studies. Almost all of the studies, except Langston and Langston (2008), Stephan and Stephan (2016) and Ristimäki et al. (2013), use process data, which as explained earlier, has a much more narrower system boundary and therefore several upstream impacts are ignored. What is also evident from the Table A1 in Appendix A is the number of question mark icons, which means that information was either not provided or is unclear. This results in a severe lack of transparency and the reader is unsure of what assumptions were made, data sets used and calculations methodologies performed. It is noted that some of this information may be alluded to by the author in previous studies, but this was not made clear from the papers included in this review.

The next key issue is that whilst most of these studies set about claim to integrate LCC and LCA data, they fail to actually provide this integration either graphically or within the text. Some of the studies that do in fact succeed with this integration through visual means are discussed above but this is a very small number of the 22 studies overall that were consulted for this review. Most studies provide their LCA and LCC results separately either in graphs or tables, such as Menzies (2010) and Leckner and Zmeureanu (2011) and still continue to separate the environmental results from the economic results in their discussion and conclusion sections. There is also a general lack of graphical output, such as Bierer et al. (2015) and Heijungs et al. (2013). Life cycle studies can be quite complex and data intensive (Zuo et al., 2017) and providing a form of graphical interpretation can better help the reader to interpret the results and also emphasise the trade-offs between environmental and economical impacts.

Another common aspect is the fact that several studies rank results into terms such as 'integrated benefit' or 'sustainability index', for example, such as Deng et al. (2008) and Savino et al. (2017). However the method behind the weighting of these results is not provided. What are the criteria for ranking one option above another? For the studies that integrate both LCA and LCC results into one graph (as discussed above), the scaling factor (i.e. how to get two quite dissimilar datasets, such as cost and GHG, onto one graph and scale) is not provided.

The next key weakness to note is that several studies either neglect to consider REE, or explicitly state that REE was not considered, such as Leckner and Zmeureanu (2011), Heijungs et al. (2013) and Hoogmartens et al. (2014). Thus failing to actually carry out a full life cycle assessment as this life cycle stage can represent up to 32% of the initial embodied energy of the building (Treloar et al., 2000b). From an LCC perspective replacement and maintenance costs are also often excluded such as in Anastaselos et al. (2009) and Savino et al. (2017). Another life cycle stage often not clarified is the operational stage. Both from an LCA perspective, such as in Langston and Langston (2008) and Huppes and Ishikawa (2005), and a LCC perspective such as Hoogmartens et al. (2014) and Bovea and Vidal (2004).

What is also be noted is a trend to carry out LCA and LCC on either products (Deng et al., 2008) or energy efficient technologies (Ristimäki et al., 2013; Leckner and Zmeureanu, 2011). There is a lack of studies that combine LCA and LCC on typical buildings, especially residential buildings, which tend to make up most of the building fabric.

Some of these studies present quite a complex and data intensive frameworks and methods, such as Heijungs et al. (2013), Petrillo et al. (2016) and Bierer et al. (2015), that are not suitable for early stage design. Implementing life cycle economic and environmental optimization at an early stage design is critical as the potential for change decreases rapidly throughout the building life cycle (Kovacic and Zoller, 2015). Lastly, some of the studies are quite inflexible with regard to personal parameters. What may be tolerable to one user will not be tolerable (either in terms of economical cost or environmental cost) to another user. There should be allowance for users of such frameworks to tailor it according to their unique requirements.

These key weaknesses provide the road map to future development of integrated LCA and LCC development. Bierer et al. (2015) states this concisely:

"There is the undisputed need for the coupling of Life Cycle Costing (LCC) and Life Cycle Assessment (LCA). However, in published studies both methods are often used in parallel or with little integration. This causes double work in data acquisition and a lack of consistency of the underlying analyses' scopes and, therefore, limits the significance of the analyses results. Further on, no mature theoretical approach for the integration of LCA and LCC exists".

2.5.2. Commercial tools

There has been an increase in LCA tools that include LCC analysis within its capabilities, and visa versa (Zuo et al., 2017). Table A2, in Appendix A, provides a detailed overview (including strengths and weaknesses) of some of the most frequently utulised commercial tools that combine both these functionalities. These tools include, but are not limited to, ENVEST 2 (BRE Group, 2016a); SimaPro (SimaPro, 2016); eTool (eTool, 2015); IMPACT (BRE Group, 2016a); TALLY (KT Innovations et al., 2016); GABi (Thinkstep, 2015); BEES (NIST, 2010) and OpenLCA (GreenDelta, 2016).

There are a limited number of studies available that critically review these tools in terms of both their integrated LCA and LCC functionalities. Most papers either provide a review of either LCA tools (Unger et al., 2004) or LCC tools (Vijayan and Kumar, 2005). Some of the studies that have assessed these integrated tools include Gluch and Baumann (2004), Haapio and Viitaniemi (2008), Hoogmartens et al. (2014), Petrillo et al. (2016) and Heijungs et al. (2010). These studies have concluded that typically these tools typically have a high level of complexity but with a low level of practicality and that there are certain points of conflict to be aware of when using both LCC and LCA functionalities simultaneously, such as system definition, treatment of time and aggregation.

2.5.2.1. Weaknesses and gaps in commercial tools

The high level of complexity is quite evident is tools such as SimaPro and GABi which, as confirmed by Han (2011) and Michalski (2015), takes a significant amount of time to master and use and are also quite data intensive. These tools are often not suitable for early stage design, when little data is available (Zuo et al., 2017). This design phase is the most critical phase which to influence and optimise the design from an environmental and economic perspective (Kovacic and Zoller, 2015).

Lack of transparency is a common critical weakness shared across all the reviewed tools. Formulae and data sets are often not provided and there is a severe lack of documentation providing the user with detailed information about the tools calculation procedures and assumptions provided to the user (Heijungs et al., 2013; myEcoCost, 2010; BuildingGreen, 2000; De Wolf et al., 2017).

Another aspect plaguing these tools, similar to the academic tools reviewed before, is the propensity to use process data for their embodied energy and GHGE estimations. As explained earlier, this approach has a narrow system boundary and neglects several upstream processes. BuildingGreen (2000) confirms that tools such as BEES make it impossible to explore any upstream impacts. Where as using an approach such as input-output based hybrid data will provide a much more comprehensive analysis of the building and products true life cycle impacts, because of a much wider system boundary.

Several tools rank their results, in terms like 'Ecopoints' (ENVEST 2) or 'Medal' (eTool, 2015). In order to rank these results a weighting or scaling factor has to be applied by the tool developer in order to determine what is the benchmark is for either a tolerable or intolerable performance (i.e. high or low Ecopoints for example). This weighting information is often not provided thus making it unclear to the user why certain project options are ranked higher than others.

These tools do not always assess the complete life cycle of the building, for example TALLY not including impacts from construction or operation (Zuo et al., 2017) or IMPACT does not include impacts from building services (BRE Group, 2016b), and fails to provide an assessment from a life cycle perspective.

Kovacic and Zoller (2015) confirmed there is a gap in developing tools able to successfully integrate both environmental and economic evaluation (with the help of LCA and LCC), particularly at an early design stage. Petrillo et al. (2016) also state that as so many tools are currently in existence, there is a greater need to highlight complementarities or potential for integration rather than the generation of even more new tools. However, a lot of work must still be done to address their key weaknesses and gaps, as summarised in Figure 2.18.

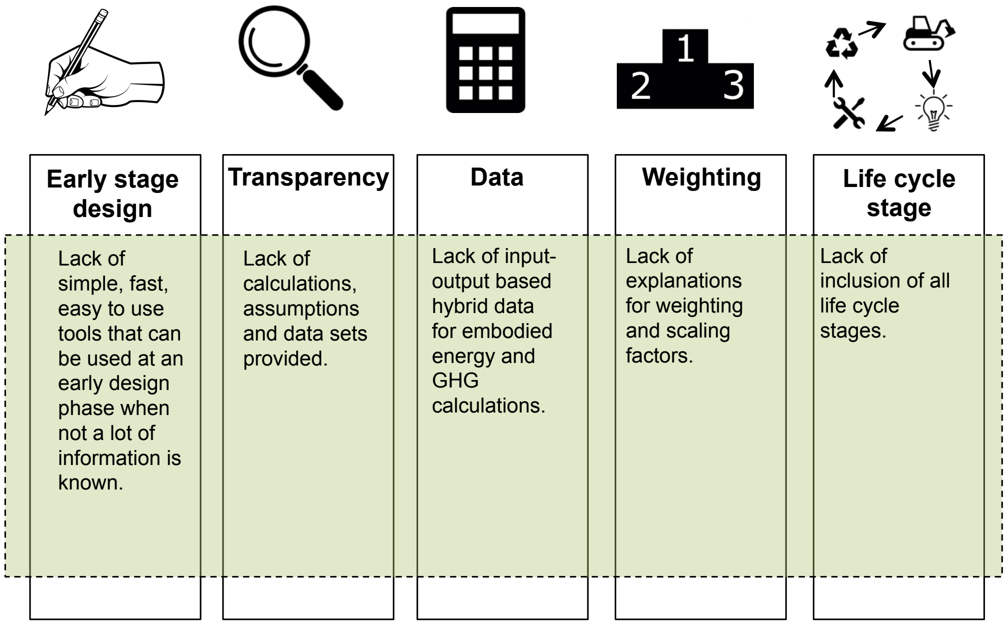


Figure 2.18 Gaps in environmental and economic commercial tools

2.5.3. The need for an environmental and economic framework for integrated building assessment

Studies such as Goh and Sun (2015) and Gluch and Baumann (2004) have emphasised the need to integrate environmental and economic assessment for a more holistic building evaluation and that there is room for improvement in new integrated tools and methods. They have identified the following three areas of research for future integrated solutions:

1. Extend the system boundaries so that the inputs of the environmental assessment can complement the economic assessment;
2. Improve the understanding of environmentally related decision-making;
3. Create new tools that involve people in the decision process.

The previous section emphasised that there is an undisputed need to couple environmental and economic assessment, often done in the form of LCA and LCC, in order to increase the uptake of life cycle based building assessment and encourage the implementation of strategies that aim to reduce these GHGE (Bierer et al., 2015). However, one of the main constraints affecting this uptake is the uncertainty towards the financial cost of this life cycle GHGE optimisation. Therefore, it was concluded that there is a critical need to start integrating both the environmental and economic analyses for buildings, from a life cycle perspective, so that the trade-offs between these two criterions can be understood, especially at an early design stage. Most of the previous studies that have aimed to integrate both LCA and LCC, have either done this by using the already established frameworks associated with LCA and LCC and conducted their building evaluation separately and then discussed the results together in the form of a conclusion (Leckner and Zmeureanu, 2011; Ristimäki et al., 2013; Bull et al., 2014; Schwartz et al., 2016). Although these studies made use of previous, well established LCA and LCC frameworks, they failed to actually integrate LCA and LCC in a meaningful way. Other studies have gone about creating new improved frameworks (such as Deng et al. (2008) and Heijungs et al. (2013)), however several weaknesses still plague this integration as discussed earlier and summarised in Table 2.7, such as lack of visual output to aid interpretation of results of lack of comprehensive quantification techniques.

Table 2.7 Key weakness and gaps of previous environmental and economic studies

Key weakness and gaps	Sources	Detail
Lack of transparent inputs and calculations	1,2,3,4,5, 6,7,8, 16, 17	All relevant inputs and calculations often not provided. This includes a detailed list of all assumptions, data sources and variables.
Incompleteness in embodied GHGE calculations	3,8,9,10, 11, 12, 13, 14, 15	Several studies made use of process analyses, which ignores several upstream impacts when compared to more comprehensive methods such as input-output or hybrid.
Lack of visually integrated LCA and LCC results	1, 3, 5, 6, 8, 9, 10, 11, 12, 13, 16, 18, 19	Either no graphic output has been provided or LCA and LCC graphs provided separately
Lack of weighting/ scaling factor explanations	2, 3, 5, 7, 17, 18	Detail and assumptions regarding the weighting or scaling factors often not explained.
Lack of recurrent embodied GHGE and replacement cost inclusion	5, 6, 7, 8, 10, 11, 16, 19, 20	Lack of comprehensive life cycle assessment as recurrent embodied GHGE and/ or replacement cost not included (or unclear if in fact included)
Lack of operational GHGE and operational cost inclusion	6, 11, 20	Lack of comprehensive life cycle assessment, as operational GHGE and/or cost have not been included.
Lack of building scale analysis	1, 2, 11	Approach not applicable to building scale analysis and more inclined for product/ material scale analysis.
Lack of early stage design application	2, 11	Information used not based on data typically available at an early stage in the design
Lack of selection process based on user personal preferences	2, 14	Users personal preferences ignored as results are often pre-determined as ‘suitable or not’ (and not dependant if in fact suitable for that particular user).

Sources: 1 Bierer et al. (2015) 2 Deng et al. (2008) 3 Gu et al. (2008) 4 Hamdy et al. (2013) 5 Heijungs et al. (2013) 6 Hoogmartens et al. (2014) 7 Huppes and Ishikawa (2005) 8 Menzies (2010) 9 Mithraratne et al. (2007) 10 Anastaselos et al. (2009) 11 Bovea and Vidal (2004) 12 Bull et al. (2014) 13 Kneifel (2010) 14 Savino et al. (2017) 15 Schwartz et al. (2016) 16 Leckner and Zmeureanu (2011) 17 Ristimäki et al. (2013) 18 Ding (2005) 19 Petrillo et al. (2016) 20 Langston and Langston (2008)

Other studies have aimed to achieve this integration in the form of new tools (Anastaselos et al., 2009; Hoogmartens et al., 2014), methods (Gu et al., 2008) or model (Bierer et al., 2015; Savino et al., 2017). However, as stated by Kovacic and Zoller (2015), the problem with life cycle studies does not stem from a need to create more tools and more methods (since so many tools currently exist), but rather to harness the methods that are already established, highlight possibilities of their integration and address critical factors such as increasing the uptake of life cycle studies and adding more comprehensive data to the field. To integrate environmental and economic assessment in the form of an improved framework provides an ideal platform from which to start this integration. A framework can be defined as a basic conceptual structure of ideas (Merriam-Webster, 2017) intended to support of guide something that expands the structure into something useful (TechTarget, 2017) (refer to Figure 2.19). It can be further defined as an outline of interlinked items which supports a specific objective and is used to plan or decide something (Cambridge Dictionary, 2017; BusinessDictionary, 2017).

Framework:

1.
a: a basic conceptual structure of ideas
b: a skeletal, openwork, or structural frame
Synonyms: configuration, infrastructure, structure, skeleton
Related words: outline, network, shape
(Merriam-Webster, 2017)

2.
A framework is a real or conceptual structure intended to serve as a support or guide for the building of something that expands the structure into something useful.
(TechTarget, 2017)

3.
A system of rules, ideas or beliefs that is used to plan or decide something.
(Cambridge Dictionary, 2017)

4.
Broad overview, outline, or skeleton of interlinked items which supports a particular approach to a specific objective, and serves as a guide that can be modified as required by adding or deleting items.
(BusinessDictionary, 2017)

Figure 2.19 Framework definition

2.5.4. Summary

This section highlighted the fact that even though there has been development in the integration of environmental and economic building assessment, both from an academic and commercial perspective, this development has been slow and there is still a significant amount of weaknesses and gaps that need to be addressed before this integration is fully achieved. By improving data techniques (such as the use of input-output based hybrid data); transparency (especially with regards to data sets, assumptions and calculations); graphical outputs; explanations of weighting factors and inclusion of all life cycle stages, this integration can be better achieved. An integration that is critically needed by building decision makers so as to ensure that both environmental and economic building aspects can be optimised at an early stage in design.

The next section provides a brief overview of some of the methods (alluded to earlier) used to aid the integration process, such as Multi Criteria Decision Making, and also discusses other integration methods like the Marginal Abatement Cost.

2.6. Methods available to aid the integration process

The previous section provided an overview of the earlier studies that have aimed to integrate LCA and LCC. A common form of integration method applied was the use of frameworks (Deng et al., 2008; Heijungs et al., 2013). A framework can be defined as a basic conceptual structure of ideas (Merriam-Webster, 2017) intended to support or guide something that expands the structure into something useful (TechTarget, 2017). It can be further defined as an outline of interlinked items which supports a specific objective and is used to plan or decide something (Cambridge Dictionary, 2017; BusinessDictionary, 2017). This section will briefly discuss some common framework development tools, like decision-trees, multi-criteria development making decision-support frameworks and network theory

2.6.1. The decision-making process

The decision-making process underpins the creation of support tools, such as frameworks. It is therefore important to have an overview of the processes involved in an often-complex task and to understand what tools are often utulised during the process. There is no unique and well-defined methodology that one can follow step-by-step from the beginning to the end of a decision aiding process (Mardani et al., 2015) and it is important to bear in mind that there may not always be a 'correct' decision among the choices available. The three key components of the decision-making practice are people, process and tools (Kiker et al., 2005). People approach a problem with a set of ingrained personal preferences and objectives. The final decision in any problem is dependant on the preferences of the decision-maker (Pohekar and Ramachandran, 2004). The decision-making process can be broken down into the following key steps, according to Majumder (2015):

1. Identifying of the objective/ goal of the decision making process
2. Selection of the criteria/ parameters/ factors/ decider
3. Selection of alternatives
4. Selection of the weighting methods to represent importance
5. Method of aggregation
6. Decision making based on aggregation results

Department for Communities and Local Government (2007), in their guidance document of developing energy policies, includes a process similar to that described above but adds the following additional final steps: Analysis of the options, make choices and provide feedback.

There are several tools available that can be used to aid the decision-making process. One such tool is the decision tree, Figure 2.20. It is a graphic technique that illustrates hierarchal interrelations. Its applicability to life cycle decisions is supported by Buchert et al. (2015), as it can be used to model process alternatives for every phase in the product lifecycle. Every time that a design parameter is set, the solution space is limited, leading to different decision pathways. The figure below provides an example of a decision tree used by Buchert et al. (2015) in which he has included three indicators upon which to base the final decision on, namely economic, social and environmental. The hierarchy is defined by the multiple tiers starting at Tier 1.

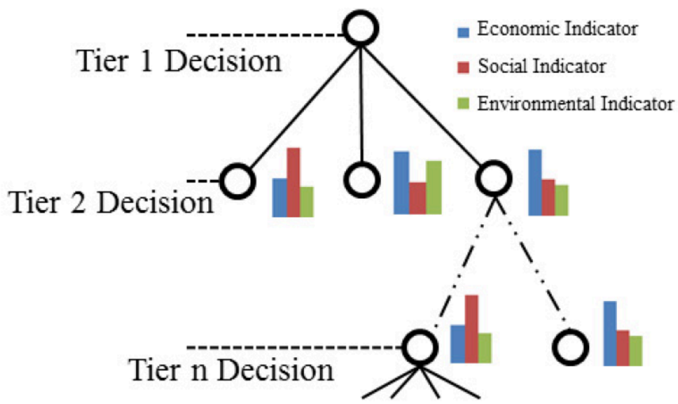
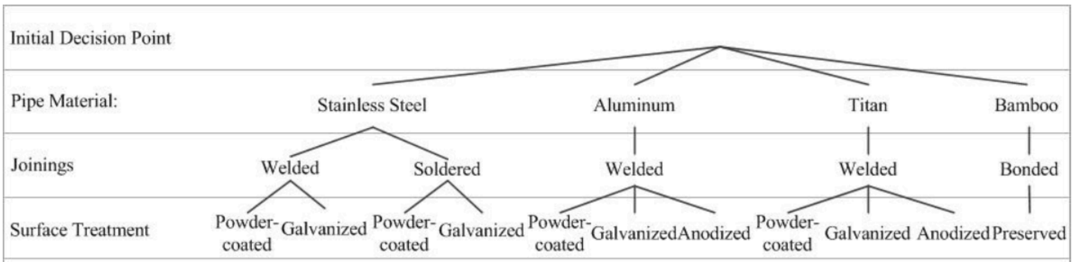


Figure 2.20 Example of a decision tree

Source: Buchert et al. (2015)

Another example of the application of a decision tree applied to a design problem is illustrated in Figure 2.21, where different frame materials for a bicycle are being evaluated and compared against multiple criteria such as monetary cost, GWP, energy demand and weight.



Monetary Cost [€]	52	162	57	167	43	153	47	325	435	329	71
GWP [kg CO_2eq]	32,9	32,9	40,6	40,6	21,1	20,8	31,3	18,0	17,0	22,9	4,3
Eutrophication [g Neq]	2,9	3,4	6,3	6,8	10,3	10,2	13,1	1,6	1,4	2,9	11,2
Acidification [H+ moles eq]	0,15	0,15	0,29	0,29	0,10	0,11	0,12	0,07	0,06	0,07	0,03
Energy Demand [Mj]	409	407	499	497	353	339	525	272	253	354	71
Weight [kg]	4,3	4	4,8	4,5	2,3	2	2	1,3	1	1	3,2

Figure 2.21 Example of a decision tree applied to a bicycle frame material selection problem

Source: Buchert et al. (2015)

From the two diagrams provided above, it is obvious that the decision is based on not only one criterion but in fact on multiple criterions. Basing a decision on multiple factors, especially in the environmental field, is quite routine as there are a multitude of contributing factors that make up the energy and environmental systems (Jato-Espino et al., 2014), and as illustrated by Wang et al. (2009) in Figure 2.22.

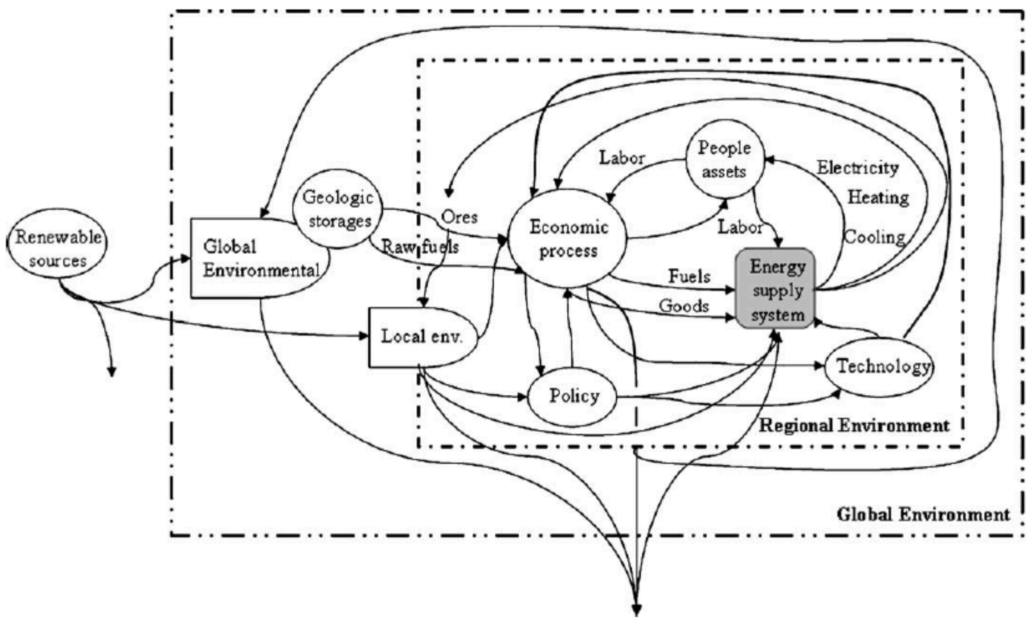


Figure 2.22 The complex interactions of the energy system

Source: Wang et al. (2009)

A tool that can further aid this decision-making process and deal with the multiple criterions required by environmental studies is called multiple criteria decision-making (MCDM). MCDM, an established branch of decision-making and a sub-discipline of operations research, is the process of making decisions in the presence of multiple objectives where the decision-maker is required to choose among quantifiable or non-quantifiable criterions (often in conflict with each other) and base the final selection on their personal preference and ultimate goal of the analysis (Pohekar and Ramachandran, 2004). The next section will provide further detail about MCDM.

2.6.2. Multi Criteria Decision Making

MCDM is a decision-making support framework that is used to evaluate multiple criteria (often both quantitate and qualitative) (Jato-Espino et al., 2014). It is often quoted as the most well-known branch of decision-making (Triantaphyllou et al., 1998). It is good for demonstrating the relationship between alternatives and relating it back to the overall goal (Mardani et al., 2015). MCDM helps to evaluate multiple options and determine the 'best alternative'. However there is typically not just one optimal solution therefore a key feature of MCDM is the necessity for the decision-maker to use their own judgement and preference in order to differentiate between solutions (Ho, 2008). An example of a MCDM framework is one often applied to the automobile industry where factors such as cost and comfort are used simultaneously to evaluate cars. Often the least expensive car will often not be the most comfortable. Hence selection of the 'best' car will be based on the users preference between cost and comfort. MCDM is widely used in the energy and environment field and in the business, economy and productions fields (Mardani et al., 2015).

MCDM is usually classified into two main categories, namely multi-criteria evaluation problems (MCEP) (where there is a finite number of alternatives explicitly known at the beginning of the process) and multi-criteria design problems (MCDP) (where the number of alternatives is unknown). Other authors have termed these two classifications as multi-attribute decision-making (MADM) and multi-objective decision-making (MODM), respectively (Zimmermann, 1991; Pohekar and Ramachandran, 2004). MCEP can further be classified into two groups namely compensatory model (which is a systematic decision-making process which evaluate each criteria which a 'trading off' scale of good and bad attributes, as defined by the user (illustrated by the car example discussed above) and outranking methods (outranking used in order to eliminate alternatives). There are also various MCDM methods which have been developed through the years and been reviewed in detail in studies by Jato-Espino et al. (2014), Velasquez and Hester (2013) and Mardani et al. (2015), and range from fuzzy sets to numerical simulations. Kumar et al. (2017) have also provided a detailed review of the different types of software that can model these methods. Methods used within the construction industry include the popular Analytic Hierarchy Process (AHP), which analyses MCDM problems according to a comparison scale (Majumder, 2015). It helps decision makers find the best alternative as suited to their goals and preferences and does not prescribe one 'correct' option (Majumder, 2015). An example is Reza et al. (2011) who used AHP within their LCA study to evaluate different flooring systems. The AHP method has often been used in LCA studies (Jato-Espino et al., 2014). Another example includes Kim et al. (2013) who used AHP for their LCC and LCA study which looked at different civil structures. The AHP process decomposition of a complex problem into a hierarchy with goal (objective) at the top of the hierarchy, criterions and sub-criterions at levels and sub-levels of the hierarchy, and decision alternatives at the bottom of the hierarchy (Pohekar and Ramachandran, 2004). AHP is easy to use and can easily adjust to fit many problems, however due to the users preference and judgement there could be inconsistencies and bias in the final selection process (Velasquez and Hester, 2013).

AHP is also often used in combination of other approaches, forming a form of hybrid MCDM method. AHP and fuzzy sets is often combined to take into account uncertainty and vagueness of data (Jato-Espino et al., 2014). Other methods include Complex Proportional Assessment (COPRAS) which provides a stepwise method aimed at ranking a set of alternatives according to their significance) and Multiplicative Exponential Weighting (MEW) which evaluates alternatives through a weighting system. Refer to Jato-Espino et al. (2014) for a more detailed discussion of the various MCDM methods used within the construction industry and to Pohekar and Ramachandran (2004) and Wang et al. (2009) for MCDM methods used within the sustainable/ energy fields. Regardless of the method used, the basic principles remain the same: Selection of criteria (must be independent of each other), selection of alternatives (must be comparable and available), selection of aggregation methods (can be an average or a function) and selection of alternatives based on ranking/ weighting (Majumder, 2015). Refer to Figure 2.23 for a diagram of the steps usually included in the MCDM framework, as defined by Kumar et al. (2017).

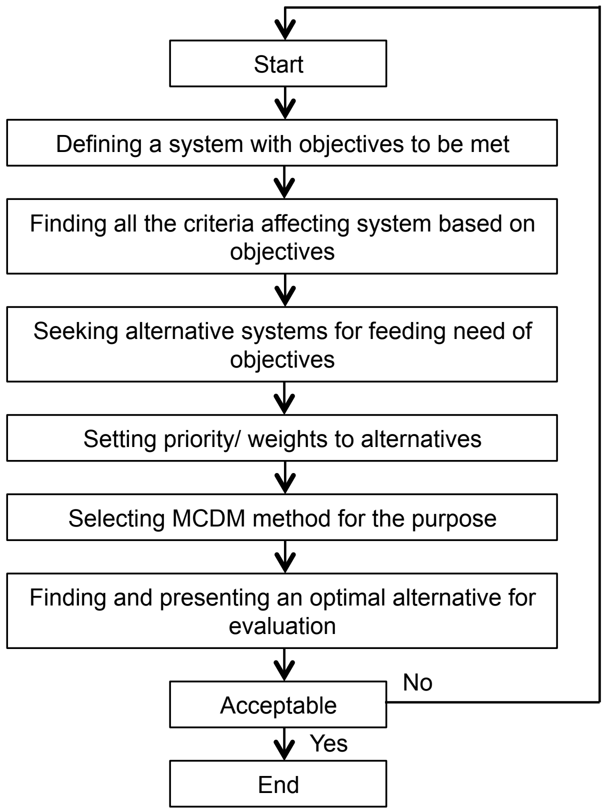


Figure 2.23 Multi criteria decision process

Source: Kumar et al. (2017)

When using MCDM it is important to be aware of the potential drawbacks associated with this technique. Such as the subjective approach due to the decision-maker's own judgement and priorities (Department for Communities and Local Government, 2007); the final outcome is limited by the scope, criteria and level of detail selected (Buchert et al., 2015); fails to take into account 'real world dimensions' such as time and behaviour and technological changes (Diakaki and Grigoroudis, 2008) and the potential to be quite data intensive (Kumar et al., 2017).

The next section will briefly discuss MCDM's use in previous environmental and economic studies.

2.6.2.1. Multi criteria decision-making in previous studies

Refer to Figure 2.24 for a list of the studies consulted and the key points and to Table A3 in Appendix A for a detailed breakdown of the studies. Studies range from Diakaki and Grigoroudis (2008), who used MCDM for evaluating and selecting energy efficient solutions for buildings, to Zopounidis and Doumpos (2002), who provided an overview of MCDM in financial decision making. MCDM is often hailed as an appropriate decision support technique in both environmental studies and economic studies, as it allows for the evaluation of complex problems, promotes the role of the participant in the decision making process, facilitates complex and comprehensive decisions and provides a good platform from which to gain an understanding of the problems and trade offs between criteria (Pohekar and Ramachandran, 2004; Zavadskas and Turskis, 2011).

Buchert et al. (2015) provided an example of MCDM applied to life cycle studies, in their suggested sustainable product development framework. Their process consisted of 7 steps and included: Define research target/ objective; define design parameters; define life cycle stage to be included; define alternatives; define indicators/criteria for the evaluation to be based upon; define data and lastly define assumption. They further emphasised MCDM applicability and necessity to early stage design in the hope that it can harness the selection and therefore the creation of more sustainable solutions. Wang et al. (2009) stated that MCDM is particularly useful for problems that involve both cost and CO_2 as some of the main criterions. Zhang et al. (2014) also used MCDM for their economic and environmental assessment of low carbon building measures. MCDM is also seen as an appropriate tool in which to explore the trade-offs between energy efficient solutions and it MCDM is often used in combination with energy simulations (Diakaki and Grigoroudis, 2008). Diakaki and Grigoroudis (2008) looked at the relationship between operational energy and cost, for energy efficient solutions such as glazing and insulation. Several studies have stated that the AHP method is the most popular in both the environmental and economic fields (Pohekar and Ramachandran, 2004; Wang et al., 2009; Ananda and Herath, 2009; Kumar et al., 2017; Zopounidis and Doumpos, 2002).

The disadvantages associated with MCDM have been identified by several of these studies. Buchert et al. (2015) stated that the level of detail and the scope on MCDM analysis can be quite subjective. Diakaki and Grigoroudis (2008) echoed this by stating that the outcome can be severely influenced by the knowledge of the decision maker and that no optimal solution exists when it comes to energy efficient solutions doe to the amount of complex and competitive criteria). While Zopounidis and Doumpos (2002) stated that for economic related MCDM problems the success can be severely influenced by the computer program selected. Wang et al. (2009) emphasised the importance of selecting a MCDM method that is appropriate to the specific design problem being assessed and that attention must be paid to the allocation of weighting and aggregation. The fact that there is no mandatory legislation or agreed upon guidance documents can further plague the successful uptake of MCDM (Kiker et al., 2005). Some of the key aspects from the previous studies are summarised in Figure 2.24.

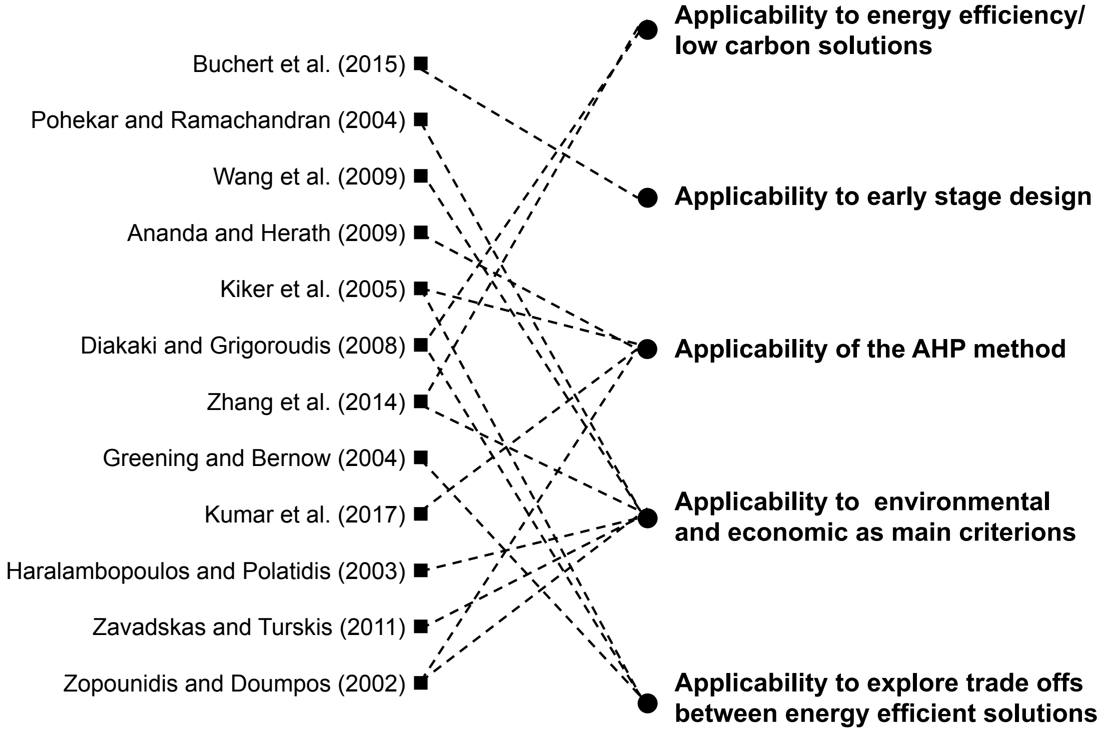


Figure 2.24 Summary of key aspects of previous environmental and economic MCDM studies

It is also important to be mindful of the gaps of these previous studies, for instance the fact that both Diakaki and Grigoroudis (2008) and Zhang et al. (2014) only considered capital cost and operational energy for their analysis of energy efficient measures, ignoring the other life cycle stages. Most of the studies also provide a more theoretical overview rather than a practical overview, the application of MCDM to building decision examples.

2.6.3. Network Theory

Network theory, also referred to as Graph theory (Konig and Battiston, 2009), provides a graphical means in which to demonstrate complex systems. Baez et al. (2012) classifies network theory as the study of complex interacting systems that can be represented as graphs equipped with extra structure. A graph is a number of vertices (V) connected by edges (E), as illustrated in Figure 2.25. Representing a problem as a graph provides a different point of view and potentially simplifies a problem. Network theory can therefore be used to complement MCDM as it can help provide a graphical output for the complex problems analysed.

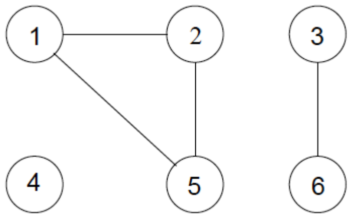


Figure 2.25 Diagram of a graph made up of vertices and edges

Source: Konig and Battiston (2009)

Examples of networks can be a model/graph that demonstrates the resource flows like energy through ecosystems or a diagram of an electrical circuit (Baez et al., 2012). Konig and Battiston (2009) also stated that network theory has been a useful approach in economic theory as it helps to diagrammatise the relationships between economic agents. There are several different types of graphs, including directed graphs, weighted graphs, bipartite graphs and trees, as illustrated in Figure 2.26. Refer to Konig and Battiston (2009) and West (2001) for a detailed overview of the elements of graph theory.

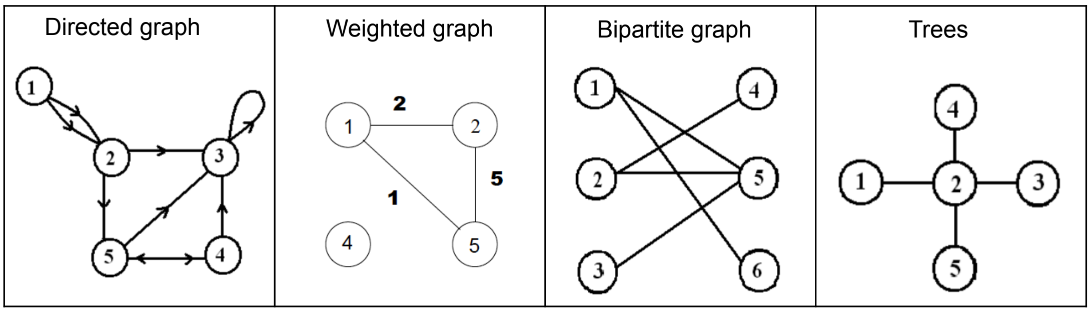


Figure 2.26 Examples of graphs

Source: West (2001)

An example of a graphic device used to aid multi-criteria decisions was complied by Torcellini et al. (2014), which analysed the economic feasibility of net zero energy buildings (USA based study). This study displayed the results graphically with the use a four-quadrant graph, as illustrated in Figure 2.27. If increasing cost, from the origin of a graph, is in the positive y-axis and energy saved is in the x-axis, the result will be in quadrant 1. The building will sit in the origin if it incurs no extra cost and is based on typical or code-mandated energy performance.

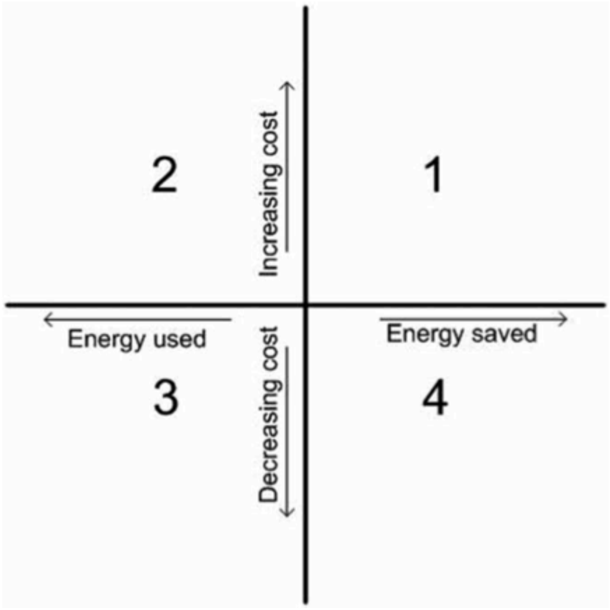


Figure 2.27 Graphical device to illustrate decision trade-offs for buildings and energy efficiency measures

Source: Torcellini et al. (2014)

Another example of a tool to help visualise two different variables but in an integrated manner was used by Stephan and Stephan (2017). Their study included the life cycle water, energy and cost analysis, divided the financial results (in terms of NPV in US cents) by the amount of water saved (in terms of kL) over the lifetime of the project. The various options being assessed (such as rainwater harvesting, RWH, and condensate water harvesting, CWH) are consequently ranked, as illustrated in Figure 2.28. Cost to the user is illustrated to the left in red and benefit (thus financial savings) is on the right in green. A method such as this to not only provides an improved understanding as to the possible environmental and economic trade-offs but also helps to address one of the key gaps of previous studies, which was a major lack of visual output (that could essentially aid the users interpretation of results).

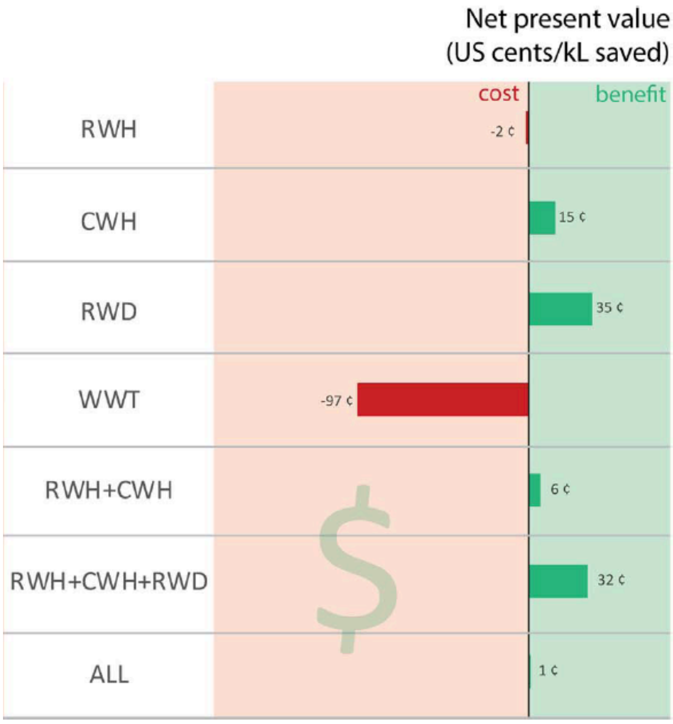


Figure 2.28 Example of integrating environmental benefit (in this case water saved) with financial cost

Source: Stephan and Stephan (2017)

Column or bar charts are one of the most common graphical outputs used in previous studies to illustrate either the environmental or economic results. Examples include Anastaselos et al. (2009), Bovea and Vidal (2004), Crawford et al. (2016) and Schwartz et al. (2016). A bar chart displays data in a series of horizontal bars whereas as the column chart displays the information in vertical bars. These types of charts are good for showing comparison, such as the LCGHGE comparison between 2 or more building design options. Bar charts are one of the most popular types of graphs and are visually strong and easy to read (University of Leicester, 2017). Another way of going about the bar chart is demonstrating the performance of the design options in comparison against the base case, thus the base case is always represented by the value zero. This technique has also been used by Stephan and Stephan (2016) who in their study illustrated the relative difference in life cycle energy and NPV of the investigated design options in comparison to the base case, as illustrated in Figure 2.29. Their results included the life cycle energy demand (LCE) (in grey on the left axis) and NPV (red values for negative and green for positive, on the right axis). The graph is split up into life cycle embodied energy

(LCEE); life cycle operational energy (LCOPE); life cycle transport energy (LCTE) and life cycle energy (LCE) and includes the comparison of measures such as photovoltaic panels (PV) and LED lighting (LED).

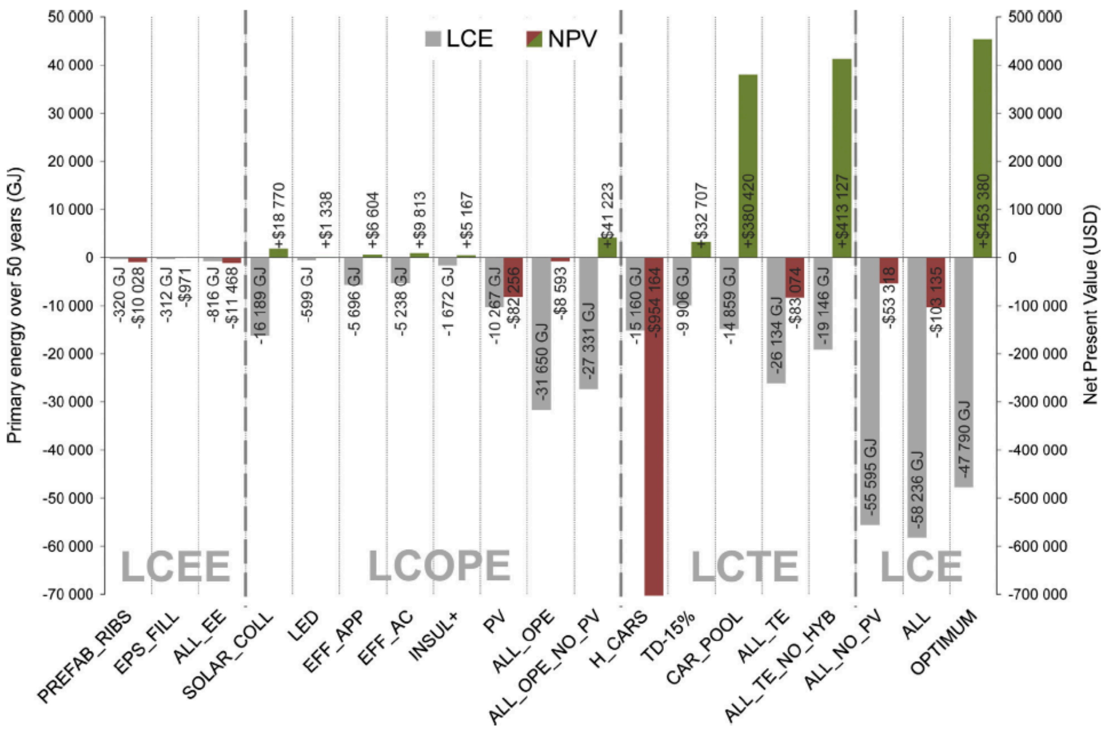


Figure 2.29 Example of bar chart illustrating the relative difference between reduction in NPV and life cycle energy demand for the investigated design options in comparison against a base case

Source: Stephan and Stephan (2016)

2.6.4. Marginal abatement cost curve

A technique regularly employed in environmental based studies is the 'Marginal Abatement Cost' (MAC) curve. It graphically demonstrates the marginal abatement costs (which is the cost of reducing environmental impacts such as GHGE) graphically in juxtaposition with the level of environmental impact (for example the amount of greenhouse gas savings). It is often used as a policy device in order to prioritise GHGE reduction options.

The MAC curve can be expressed as follows: the width corresponds to the total emissions reduction available and the height corresponds to the cost effectiveness. Figure 2.30 below is an Australian based example from Pears (2016), which demonstrated that energy efficient solutions for buildings (the items in blue below that have a negative cost) can actually save the Australian government money.

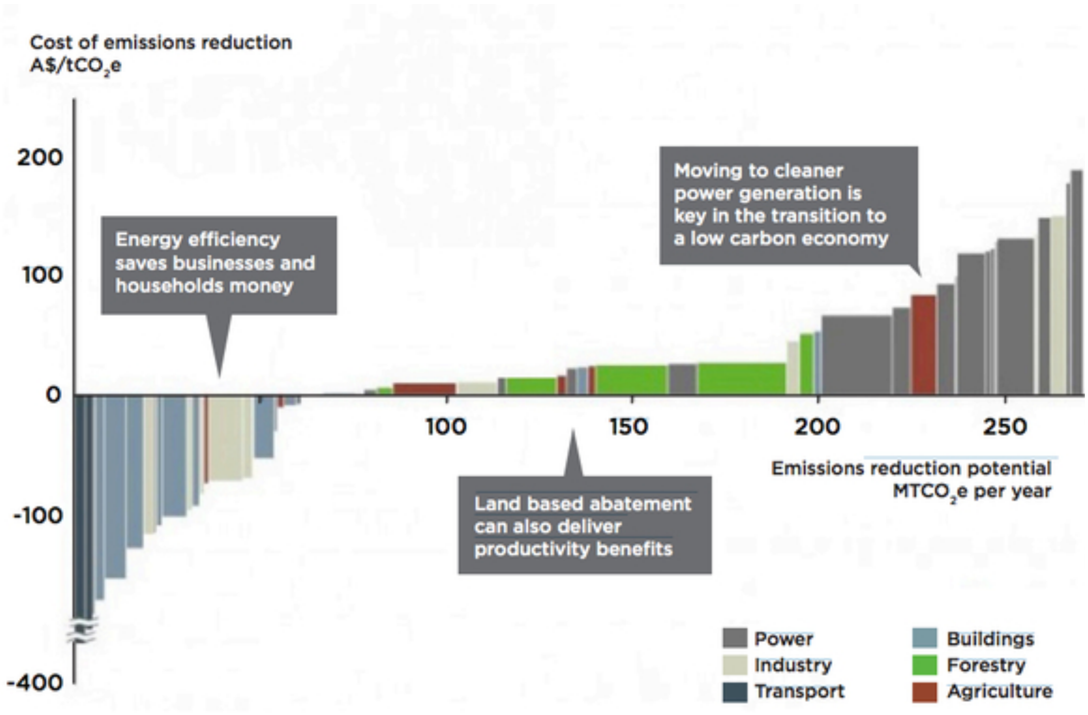


Figure 2.30 MAC curve for emission reduction strategies for Australia

Source: Pears (2016)

The MAC curve is a useful technique for graphically combining the issues of cost and GHGE. However, they are predominantly used for operational emission related studies and thus ignoring embodied or life cycle emission aspects. It has been suggested that there is merit in the integration of embodied emissions into a "robust and single ranking module" that will facilitate a more holistic view of environmental impact of emissions abatement options (Ibn-Mohammed et al., 2013).

There is also a range of issues to be mindful of when interpreting results. Issues include the transparency of results (assumptions used in the calculations have to be provided); their inability to capture interactions and interdependencies with the wider energy system; the wide range of estimates, and inaccurate ranking (Ibn-Mohammed et al., 2013).

There are several decision-making tools that have not been discussed in detail in this section. Such as the systematic approach, as opposed to the analytical approach, which as Rosnay (1979) states, includes the totality of the elements in the system, as well as their interaction and interdependence and provides a logical and ordered approach to problem solving. Another tool is cost-benefit analysis where the costs and the potential benefits of a project are analysed and selection is then based on the greatest net benefit. A further example is a feasibility study, which helps to analyse if a project can actually be achieved. However this section did provide background to the decision-making process and provided a brief overview of the popular decision-making support tool, namely Multi-Criteria Decision Making (MCDM), used in previous studies. An example of the MCDM process was described and its applicability to environmental and economic studies was discussed. Some gaps on these earlier studies were highlighted such as the fact that not all life cycle stages are considered and that most studies remain at quite a theoretical point of view. This was followed by the complementary graphic approach of network theory.

2.7. Summary

A number of key aspects were addressed in this chapter, as illustrated in the diagram in Figure 2.31. First of all there is a need to address the embodied energy and GHGE in buildings and, not only the operational energy and GHGE (as previously dealt with in policy, industry and literature). Secondly, there is a need to address this from a life cycle perspective in order to ensure that improving the embodied performance does not have a negative affect on the operational performance from a building (refer to Section 2.2). Several studies and voluntary standards, whilst promoting the assessment of embodied energy but rarely make reference to the importance of looking at it in conjunction with other life cycle stages. One such method to take forward for this analysis is called life cycle assessment (LCA) (refer to Section 2.3). Thirdly we need to help counteract the barriers affecting the uptake of embodied GHGE reduction. One such barrier that has not been dealt with extensively yet in literature yet is the uncertainty of financial cost. Several efforts have been made to help quantify the financial costs from an operational perspective, leaving the embodied perspective largely ignored. To help quantify the economic performance of including the embodied and operational energy and GHGE reduction in building, a life cycle costs (LCC) analysis method can be utilised (refer to Section 2.4). Concentrating on one building phase, being capital cost, which is so often found in previous studies is avoided. And lastly, there is a need to consolidate the results of these two methods, LCA and LCC, so that both the environmental and economic performance of the building can aid the decision-making process. By combining the outputs of these two methods, the trade-offs and the relationship between economic and environmental cost can be made more apparent. As previously stated by studies, such as Goh and Sun (2015), new building solutions must be able to link environmental issues with financial consequences. There has been an increase in studies and tools that aim to integrate LCA and LCC (refer to Section 2.5) in the form of new frameworks or models, but several weaknesses and gaps that still need to be addressed, as outlined in the diagram below. These gaps provide a road map for future LCA and LCC integration. There are also several methods available to aid this integration process, such as MCDM (refer to Section 2.6). This leads to the research questions that form part of this study, as explained in the following section.

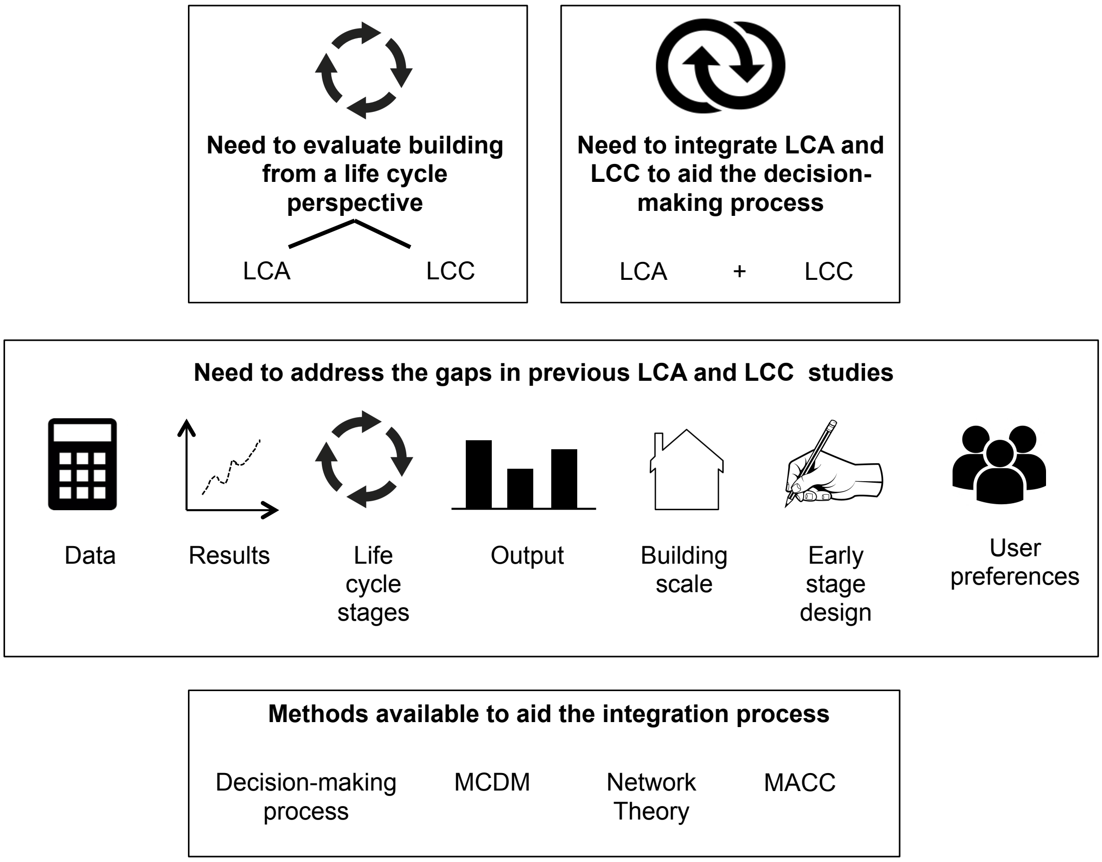


Figure 2.31 Summary of key points of the literature review

2.8. Research questions

The previous section highlighted the fact that there is an urgent need to assess a building's environmental performance from a life cycle perspective and to integrate this assessment with its expected economic performance. By having both the environmental and economic performance available, particularly at an early design stage, the trade-offs between both these aspects can be used to assist the decision-making process. The previous chapter also discussed assessment approaches associated with these methods, namely LCA and LCC, and provided an overview of the present status of their integration. This section concluded with the observation that there are still several gaps and weaknesses that have to be addressed in order to provide a more comprehensive assessment. This leads into the research aim of this study, which is to develop a framework that facilitates the evaluation of a building, based on both its environmental and economic performance at an early design stage. In order to address this aim the following research questions are proposed and have been addressed in the following chapters:

1. What are the most appropriate decision-support approaches to aid environmental and economic building related decisions?
2. What are the most appropriate environmental and economic assessment techniques?
3. How can the environmental and economic assessment of buildings be integrated into a single framework for comprehensive building evaluation?

3.

Research Design

3.1. Introduction

The previous chapter examined the importance of assessing GHGE from a life cycle perspective and the critical need for integrating economic implications into these assessments, for a more holistic evaluation of building performance. The availability of both the environmental and economic performance, especially at an early design stage, the trade-offs between both of these aspects can be used in the decision-making process, resulting in the selection of more sustainable building solutions. However, as demonstrated by the review of earlier academic studies and commercial tools, several weaknesses and gaps plague the integration of environmental and economic assessment, especially from a life cycle perspective. This can have significant influence on the decision-making process. Several environmental and economic approaches were discussed in Chapter 2, ranging from the well-established LCA and LCC quantification methods to the decision-making process frameworks such as MCDM. Gaps in these previous studies were accentuated, for example not all life cycle stages are considered and that most studies are at a relatively theoretical level. These gaps and weaknesses create a roadmap for future integrated environmental and economic framework development, as illustrated in Figure 3.1.

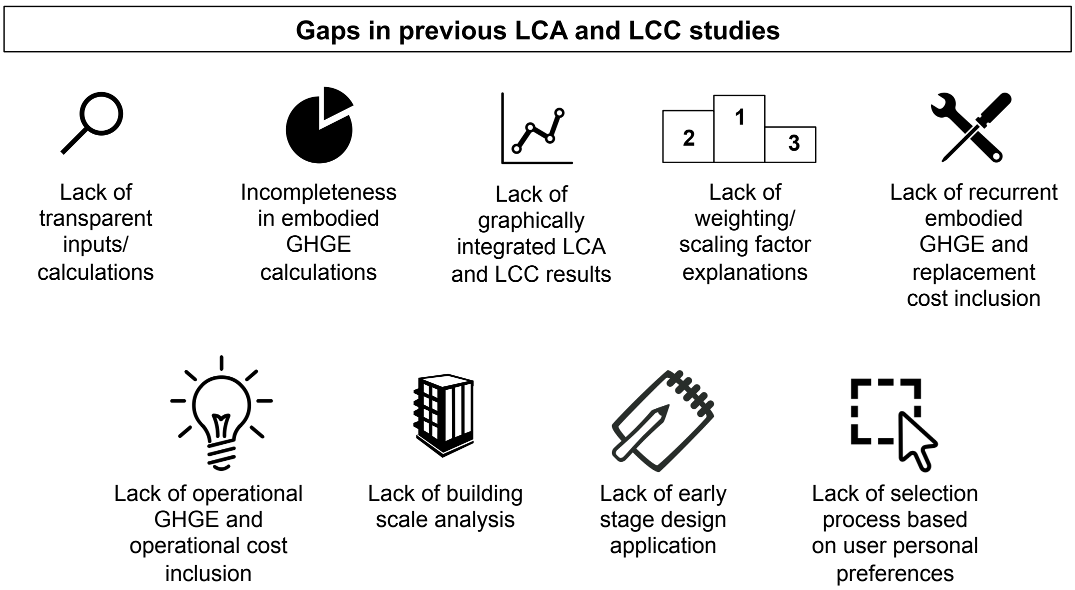


Figure 3.1 Gaps in previous environmental and economic studies

This leads to the research aim of this study, which is the development of a framework that allows the evaluation of a building at an early design stage, based on both its life cycle environmental performance and life cycle economic performance. This chapter provides an overview of the steps that were included to address the research aim and the research questions as outlined in Chapter 2.

This chapter includes an overview of the three research design steps that form part of this study, followed by a detailed description of each step.

3.2. Research design steps

In order to address the research questions outlined in Chapter 2, the following key research design steps were required, as set outlined Table 3.1:

Table 3.1 Research questions and research design steps

Research questions		Research design steps	
1	What are the most appropriate decision-support approaches to aid environmental and economic building related decisions?	**1**	Select appropriate decision-support frameworks to assist environmental and economic building related decisions (Section 3.3)
2	What are the most appropriate environmental and economic assessment techniques?	**2**	Select appropriate environmental and economic assessment techniques (Section 3.4 and 3.5)
3	How can the environmental and economic performance of buildings be integrated into a single framework for comprehensive building evaluation?	**3**	Select appropriate methods available for the integration of environmental and economic performance to facilitate comprehensive building evaluation (Section 3.6)

The next section discusses each research design step in more detail.

3.3. Select appropriate decision-support frameworks

This section has been divided into two parts. The first part selects the appropriate environmental and economic framework approaches used for this study, followed by the decision-support framework that has been selected.

3.3.1. Select appropriate environmental and economic framework approaches

Chapter 2 provided an overview of the various methods available to assess the environmental and economic performance of buildings. In Section 2.3, it was stated that environmental assessment could be broadly classified into three categories, being performance based design, sustainable rating schemes and LCA (Bragança et al., 2010). This section concluded that only the LCA method, in comparison to the others, provided a comprehensive approach for evaluating building's environmental performance based on all relevant life cycle stages. LCA is also widely acknowledged as an appropriate method for evaluating and comparing environmental impacts of building designs (Cooper and A.Fava, 2006; Menzies et al., 2007; Heijungs et al., 2010; Chau et al., 2015) and has been extensively used in both energy and GHGE building analysis (see Section 2.3.4 and Section 2.3.5). For this reason LCA has been selected for this study's environmental assessment approach.

There is no mandatory legislation regulating LCA methodology but voluntary standards such as the International Organisation for Standardisation's 'Environmental Management – Life Cycle Assessment – Requirements and Guidelines' (ISO 14044, 2006) suggests a framework. This framework includes four key LCA steps (which have been explained in more detail in Chapter 2, Section 2.3.1.3) and illustrated in Figure 3.2. These steps include goal and scope definition (step 1); inventory analysis (step 2); impact assessment (step 3) and interpretation (step 4). What is apparent from this framework is the lack of a sensitivity analysis step after Step 4 (though it is alluded to but not specifically stated).

Life cycle studies are very subjective and include a range of assumptions have a significant impact on the final result, rendering the need for a sensitivity analysis critical (Menzies et al., 2007; Dixit et al., 2010). Another aspect to consider is that LCA also tends to be completed towards the end of the design phase, having less potential to influence design choices, and are seen as quite complex and data intensive (Crawford, 2011). There is a need therefore to integrate LCA at an early design stage and to provide improved user-friendly frameworks.

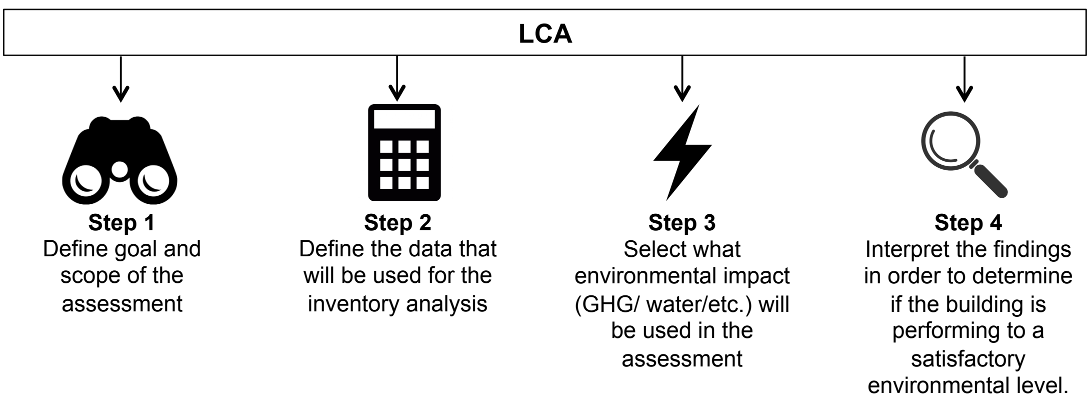


Figure 3.2 Life cycle analysis framework

Source: ISO 14044 (2006)

Chapter 2 also provided an overview of the various approaches used in the economic assessment of buildings (see Section 2.4). This section accentuated the fact that most studies and quantification approaches tend to focus only on either the operational cost perspective (see Section 2.4.1.1) or initial cost perspective (see Section 2.4.1.2) only. The initial cost phase tends to dominate building design decisions, however this phase has been demonstrated to represent only about ±50% of costs during the building lifetime (see Section 2.4.1.3) (depending on, for example, building type, location, materials and users). LCC analysis method provides a means to counteract this and include all relevant life cycle stages (i.e. initial, operational and replacement costs) in order to provide a more comprehensive form of analysis (Goh and Sun, 2015). It has also been widely used in similar studies for building economic evaluations, such as Morrissey and Horne (2011), Leckner and Zmeureanu (2011), Ristimäki et al. (2013) and Bull et al. (2014). For the reasons aforesaid, LCC has been selected for this study's economic approach to building evaluation.

Similar to LCA, LCC is not mandatory for building assessment and has no universally accepted protocol, however voluntary standards such as ISO 15686 suggest the following framework, as illustrated in Figure 3.3: define alternative strategies to be evaluated (step 1); identify economic criteria (step 2); obtain and group significant costs (step 3); perform a risk assessment, often referred to upon as a sensitivity analysis (step 4). Similar to LCA, several studies have highlighted the amount of uncertainty involved with LCC studies as the future is being forecast based on the current data and knowledge (Flanagan et al., 1989; Islam et al., 2015a). It is also apparent from this suggested framework is that step 1 should ideally be preceded by defining the goal and scope of the study (similar to LCA) and should also involve a step of defining the base case strategy against which the alternative strategies should be compared. It is therefore evident that both LCA and LCC frameworks, usually performed in isolation of each other, require further development in order to harness their true potential and address potential weaknesses.

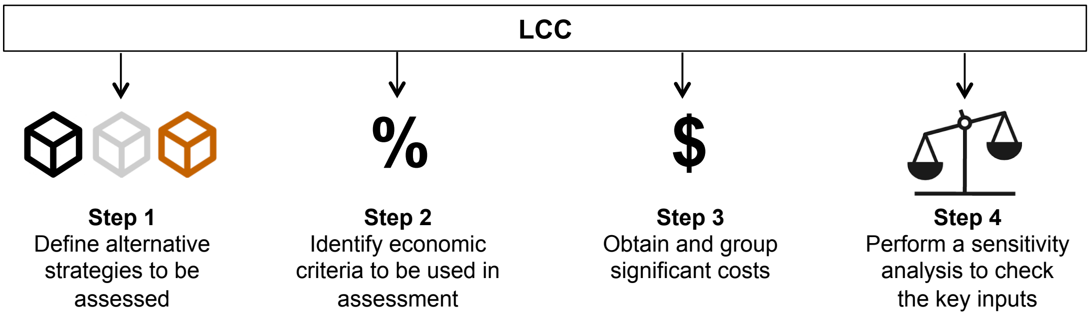


Figure 3.3 Life cycle cost analysis framework

Source: ISO 15686 (2011)

As noted earlier, most previous studies use the frameworks and related quantification techniques and data methods already associated with established LCA and LCC frameworks, such as Leckner and Zmeureanu (2011), Ristimäki et al. (2013) and Schwartz et al. (2016) (see Section 2.5). This builds upon the existing strengths of previous life cycle methodologies and harness what has already been established, instead of attempting to create new tools and methods (Kovacic and Zoller, 2015). Future integrated LCA and LCC frameworks needs to not only include these established frameworks (as illustrated in Figure 3.2 and Figure 3.3), but also address their shortcomings, together with identifying a technique to integrate them into one single framework. This study has thus selected these established LCA and LCC frameworks to form part of the environmental and economic building evaluation. The integration of these two frameworks is discussed in greater detail in Chapter 4.

3.3.2. Select appropriate decision-support framework

As discussed in Chapter 2, a key future research area for LCA and LCC integration relates to creating a means to involve people in the decision process (Goh and Sun, 2015; Gluch and Baumann, 2004) (see Section 2.5.3). There are several ways to achieve this, as discussed in Section 2.6.1. One approach, identified in Chapter 2, was the implementation of steps often associated with the actual decision-making process, as illustrated in Figure 3.4. The process, as defined by Majumder (2015), includes six key steps: identify the goal; select the criteria; select the alternatives; select the weighting methods; select the aggregation method; make the final decision.

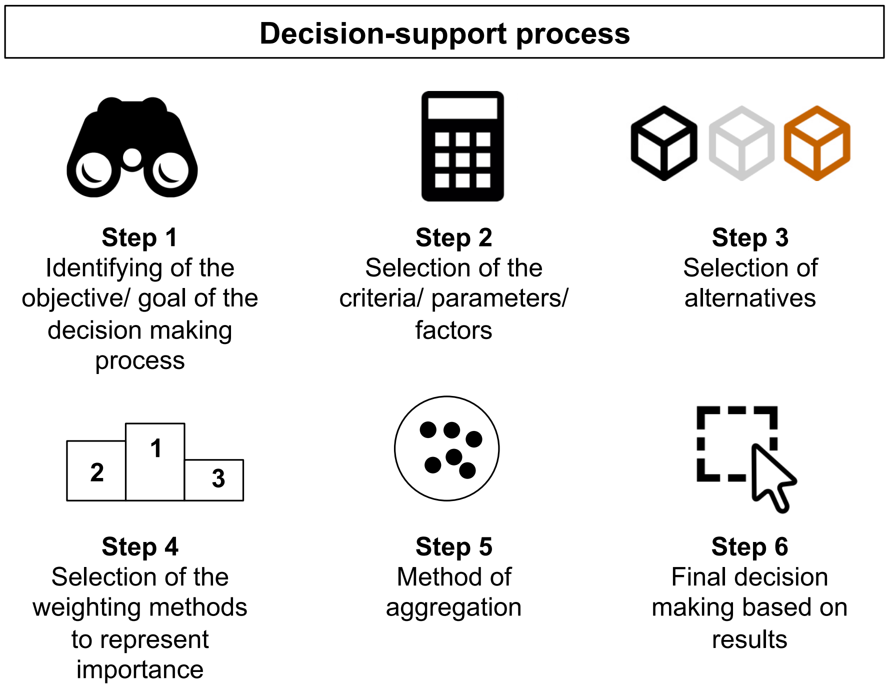


Figure 3.4 Decision-support process framework

Source: Majumder (2015)

It is important to bear these steps in mind in the development of any decision support aids, therefore such steps have been selected to integrate this decision-support process into this study's framework (as discussed in more detail in Chapter 4).

A decision-making support framework discussed in detail in Chapter 2 is MCDM (see Section 2.6.2). MCDM is good for: complex problems with multiple criteria; demonstrating the relationship between alternatives; dealing with both quantitative and qualitative data and capability provides the capability of basing the final selection on the decision-maker's personal preferences (Jato-Espino et al., 2014; Ho, 2008; Mardani et al., 2015). An example of a life cycle study, provided in Chapter 2, that used MCDM for their LCA and LCC analysis for buildings was Schwartz et al. (2016), further demonstrating its applicability to study's research focus. MCDM approach is applicable to this study's multiple criterions, being environmental and economic, as it can demonstrate their relationship and the different trade-offs (a necessary part of this study's research aim). This approach involves the user in the decision-making process (a key future research area for LCA and LCC development). For the reasons aforesaid, MCDM has been selected to form part of this study's framework.

The MCDM is broadly made up of seven key steps, starting with the defining of a goal and ending with the selection of the appropriate option, as illustrated in Figure

3.5. There are several methods associated (as per Step 5) with MCDM, however as discussed in the review of previous environmental and economic MCDM studies in the previous chapter, the AHP method is the most widely used (Majumder, 2015; Ananda and Herath, 2009; Kumar et al., 2017) and has accordingly been selected for this study.

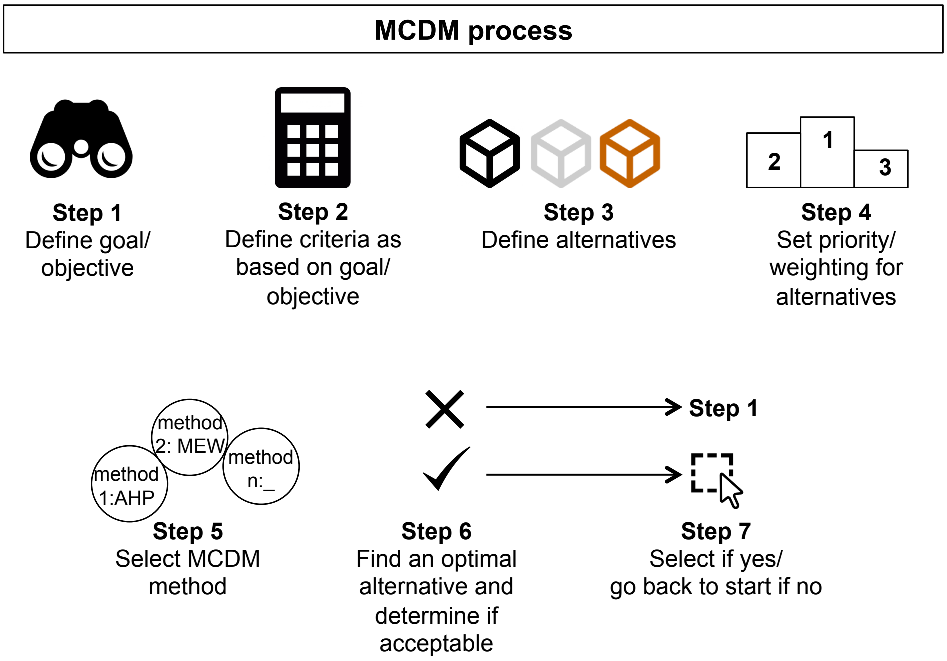


Figure 3.5 MCDM framework

Source: Kumar et al. (2017)

The review of previous environmental and economic MCDM studies (see Section 2.6.2.1) demonstrated that this decision-support framework is applicable to a range of factors such as low carbon building evaluation; early stage design; inclusion of both environmental and economic criterions and the exploration of trade-offs between energy efficient solutions. The review indicated that two key gaps were found in previous environmental and economic MCDM studies, namely the fact that the whole life cycle is frequently not considered from both an environmental and economic perspective (Diakaki and Grigoroudis, 2008; Zhang et al., 2014), and the fact that most of the studies remain on a theoretical level and are not applied to a practical built environment example (Pohekar and Ramachandran, 2004; Ananda and Herath, 2009). It is important to address these gaps in this, and any future MCDM studies.

When using MCDM it is important to be mindful of the fact that there is no 'optimal' solution, as the outcome of the analysis is defined by the decision-maker's own judgment and selection of the objective; scope and criteria (Ho, 2008; Buchert et al., 2015).

The frameworks selected above, being the LCA, LCC, decision-support process and MCDM, form the basis of this study's integrated environmental and economic framework and answer this study's first research question. Their integration is discussed in greater detail in Chapter 4, which provides more information pertaining to the development of this study's framework.

The following section provides an overview of the environmental, followed by the economic, quantification techniques selected for use in this study.

3.4. Select appropriate environmental quantification techniques

As discussed in Section 3.3.1, LCA has been selected as this study's environmental evaluation approach. In order to narrow the scope of this study, due to time and data constraints, greenhouse gas emissions (GHGE) have been selected for the environmental impact category. This also addresses one of the gaps of previous studies as there is a lack of life cycle GHGE (LCGHGE) studies. The majority of studies focus only on energy (such as Anastaselos et al. (2009), Bierer et al. (2015), Deng et al. (2008) and Hamdy et al. (2013)). With GHGE on the rise (IPCC, 2014), with an increase in legislation and a global call for GHGE reduction, such as the Paris Climate Agreement (United Nations, 2017), there is a desperate need for further understanding as to how to decrease a building's GHGE.

To deal with this study's primary focus on GHGE, a streamlined LCA approach has been used (as discussed in Section 2.3.1.1). Within this streamlined LCA approach (i.e. focus on one environmental flow only), all environmental flows other than GHGE (such as water) have been omitted, making the analysis less time and data intensive. The LCGHGE system boundary includes the initial and recurrent embodied GHGE and the operational GHGE. The end of life stages, including demolition, disposal and recycling have not been considered in this analysis due to a limited amount of data available with regard to these life cycle stages (Moncaster and Song, 2012) and as they have been shown to represent less than 1% of the building's life cycle energy requirement (Crawford et al., 2010; Crowther, 1998).

For the inventory analysis, a critical step in calculating the embodied GHGE, there are three main calculation methods (see Section 2.3.1.3), namely process, input-output and hybrid. It has been demonstrated that, of these approaches, the Path

Exchange hybrid approach provides the most comprehensive analysis of a building's environmental performance. In comparison, process and input-output analysis, are typically characterised by incomplete and unreliable results (Treloar, 1997; Treloar, 2007; Crawford, 2008).

In order to answer the environmental quantification section of the second research question, Path Exchange hybrid approach has been selected and has been described in more detail in the following calculations.

3.4.1.1. Initial embodied greenhouse gas emissions calculation method

The initial embodied GHGE (IEGHGE) of a building refers to the GHGE associated with the extraction of raw materials and manufacturing of a building material or product and construction. Calculating the IEGHGE content of every single aspect of a building can be a very time consuming and data intensive task. A building is a complex system consisting of numerous small and large components. Table 3.2 sets out the key elements should be included in this calculation (as selected for this study), in order to narrow the scope of the assessment.

Table 3.2 Key building elements to be included in embodied greenhouse gas emissions calculations for the assessment of buildings

Building element	Detail	Description
Substructure	Ground floor	The substructure has been estimated to account for a significant percentage of a building's structural embodied emissions (Crawford, 2013; Pearlmutter et al., 2007; De Wolf et al., 2015; Stephan and Stephan, 2016). The substructure has also been identified as one of the 'embodied carbon critical elements' according to RICS (2012).
Superstructure	Roof External Walls Internal walls Upper floor slabs	The superstructure has been estimated to represent over 40% of a building's structural material embodied emissions (De Wolf et al., 2015). These elements also represent a significant proportion of overall building costs. The superstructure has also been identified as one of the 'embodied carbon critical elements' according to RICS (2012).
Internal finishes	Wall finish Floor finish Ceiling finish	The finishes represent a smaller percentage of a building's initial embodied performance, but can be costly, potentially requiring frequent

Building element	Detail	Description
		maintenance and thus high recurrent energy (Stephan and Athanassiadis, 2017). The finishes have also been identified as one of the 'embodied carbon critical elements' according to RICS (2012).

The limitation of excluding certain building elements from the assessment must be taken into account. Heinonen et al. (2016) states that the cut-off criteria (and boundary definition) can affect the final results, however the exact amount of uncertainty associated to this is unclear. They further state that most building LCA seldom cover 100% of the construction materials and activities due to the limited amount of data available.

The Path Exchange hybrid method has been used to calculate the IEGHGE, as described by Crawford (2011) in Equation 3.1. The initial embodied energy (IEE) is calculated first and is thereafter converted to GHGE terms (see Equation 3.6). IEE of a material is dependent on the type of material, quantity of material and its respective embodied energy coefficient. The following steps are required to determine the total IEE of a building (IEE_b). Firstly, the quantity of the material being assessed is estimated. Secondly, this quantity (Q_m) is multiplied by what is termed the embodied energy coefficient (EC_m). Thirdly, in order to take into account the amount of materials that are wasted on site a wastage coefficient (W_m) is further multiplied. These three steps are carried out for each material contained within the building. The sum total of the individual material IEE results provide the total material based sum IEE for the building. To complete the system boundary, the total energy requirement of the building sector (TERBS) (extracted from input-output model) is determined, minus the total energy requirements of the material production processes for which process data is available (TER_m), multiplied by the building cost (C_b).

$$IEE_b = \sum_{m=1}^{M} \left(Q_{m,b} \times EC_m \times W_m\right) + \left(TERBS - \sum_{m=1}^{M} TER_m\right) \times C_b$$

Equation 3.1

Where:

IEE_b =	*Initial embodied energy of building b, GJ*
Q_m =	*Quantity of material min building b in functional unit, tonne/m/m^3/m^2*

EC_m =	*Hybrid embodied energy coefficient of material m, GJ per functional unit*
W_m=	*Wastage coefficient of material m*
TERBS =	*Total energy requirement of building sector (i.e. residential/ commercial etc.) construction-related input-output sector n, GJ/AUD1000*
TER_m =	*Total energy requirement of the material production processes for which process data is available, GJ/AUD1000*
C_b =	*Cost of building in currency units, AUD*
Source: Crawford (2011)	

The following section describes the data inputs used for Equation 3.1, in greater detail.

Quantity of material ($Q_{m,b}$)

This is extracted from the bill of quantities (BOQ) of the building being assessed. This can either be extracted from an actual BOQ (if available for a built project) or extracted from a software program such as Revit. The use of Building information Modelling (BIM) systems such as Revit is becoming increasingly popular for generating BOQ as a result of to their time efficiency and improved reliability (Abanda et al., 2015; Nadeem et al., 2015). The type of building elements that need to be quantified have been provided in Table 3.2.

Embodied energy coefficient of material (EC_m)

The embodied energy coefficient is a value for the amount of energy needed to manufacture a specific material and the production technology used. These coefficients are available from a number of sources, such as the process-based Inventory of Carbon and Energy, University of Bath, 2008. For this study, process and input-output-based data has been integrated at a material level to provide hybrid embodied energy material coefficients established using the Path Exchange hybrid method. These cover the direct inputs and outputs of the manufacturing process as well as all inputs and outputs upstream of the material manufacturing stage (Crawford, 2011). This ensures that the system boundary is complete for the individual materials, thereby avoiding the upstream truncation inherent in process-based coefficients. The only available hybrid material coefficients for Australia, were developed by Treloar and Crawford (2010) (which are based on 1996-1997 input-output data for Australia). These have been established by Equation 3.2 below. This database relates specifically to the Australian construction sector and is based on the latest available energy based input-output data available at the time of this study's publication. These should ideally be replaced by updated coefficients as and when they become available. Refer to Table B5 in Appendix B for the coefficients used.

Equation 3.2

$$EC_m = PER_m + \left(TER_m - \sum_{i=1}^{I} DER_i\right) \times C_m$$

EC_m = *Hybrid embodied energy coefficient of the basic material, GJ/unit of material*

PER_m = *Material process energy requirement, GJ/unit of material*

TER_m = *Total energy requirement of the input-output sector n to which the material belongs, GJ/ AUD1000*

DER_i = *Direct energy requirement of the input-output pathways representing the material production processes for which process data is available, GJ/AUD1000*

CP_m = *Cost of the basic material, AUD*

Source: Crawford (2011)

Wastage coefficient (W_m)

It is common practice within the building industry to order excess materials, resulting in the on-site waste of materials. In order to take this into account a wastage coefficient (W_m) was applied to the physical quantity of materials. An example of these coefficients, extracted from Crawford (2004) and CSIRO (1997), is shown in Table 3.3.

Table 3.3 Wastage coefficients

Material	Wastage coefficients	Material	Wastage coefficients
Concrete	1.15	Steel	1.05
Glass	1.03	Insulation	1.10
Paint	1.05	Timber	1.05

Source: Crawford (2004)

Total energy requirement of sector (TERBS)

This value indicates the total energy requirement for the provision of any product or service within an economy based on the total energy requirement of the relevant sector from the energy based input-output model. In other words, it is the total quantity of energy required to produce an average product from the sector in units of inputs (GJ) per dollar of sector output. By way of example, for the Australian residential building sector this value is 10.633 GJ/AUD1000 and for the commercial sector it is 9.979 GJ/AUD1000, as based on 1996-1997 energy based input-output data for Australia (Crawford, 2011).

Total energy requirement of material $\sum_{m=1}^{M}(TER_m)$

This value will depend on the type of building sector being assessed (for example residential or commercial and the relevant materials). These values are required in order to avoid double counting. This value is determined for the input-output pathways for which physical materials quantities are available. These values are based on the latest available energy based input-output model for Australia (Treloar and Crawford, 2010).

The remainder ($TERBS - \sum_{m=1}^{M} TER_m$)

By deducting the sum of the total energy requirements (TER) of the input-output sectors covering the materials contained within the assessed building, from the total energy requirement of the building sector (TERBS), the remainder, covering all otherwise unquantified processes, can be calculated (Crawford, 2011). This value will depend on the relevant input-output sector for building being assessed (TERBS) and the type of materials being used (TER_m).

Cost of building (C_b)

The cost of the building can either be supplied directly by the user, if known, or can be extracted from cost guides or databases such as Rawlinsons (2017), which provides the price per square meter (m^2).

To ensure consistency with the input-output data used, costs must be converted to the equivalent time period of the input-output data. As the latest available energy based input-output data is based on 1996/1997 input-output model for Australia (Treloar and Crawford, 2010), current building prices have to be converted to 1997 equivalent terms. In order to do this a building cost index can be used. An example of the building cost index for Melbourne is provided in Table 3.4. Such a cost index can be applied using Equation 3.3

Table 3.4 Building cost index for Melbourne, Australia

Year	Building cost index	Source
1997	144	*Rawlinsons (2017)*
2017	283	

The following equation was used to convert current prices to 1997 equivalent prices.

$$SC_b = \frac{Index\ 1997}{Index\ 2017} \times 2017\ Cost$$

Equation 3.3

Where:

SC_b = Specific cost of building, AUD/m^2

Index 1997 = Building cost index 1997

Index 2017 = Building cost index for current year

2017 Cost = Current cost of building, AUD/m^2

Source: Rawlinsons (2017)

For an Australian based study of this nature, the cost of the building is based on a rate of AUD/m^2, which is then multiplied by the gross floor area of the building (GFA), as per Equation 3.4, to calculate the total cost of the building (C_b).

$$C_b = GFA_b \times SC_b$$

Equation 3.4

Where:

C_b = Cost of building, AUD

GFA = Gross floor area of building b, m^2

SC_b = Specific cost of building b, AUD/m^2

Source: Stephan (2013)

3.4.1.2. Recurrent embodied greenhouse gas emissions calculation method

The recurrent embodied GHGE (REGHGE) refers to the GHGE related to the maintenance, repair, replacement and refurbishment of buildings. Calculating the REGHGE of every single building component is very time consuming and data intensive and can be narrowed down as set out in Table 3.2 above. The REGHGE is dependent on the building materials and components being replaced and their rate of replacement. Elements such as weather, deterioration or obsolescence can affect the replacement rate. The recurrent embodied energy is calculated first and then converted to equivalent GHGE terms.

Equation 3.5, based on the Path Exchange hybrid methodology has been used for the quantification of REE, as demonstrated in Stephan and Crawford (2015), Stephan et al. (2012) and Rauf and Crawford (2013). The period of analysis (POA) is divided by the service life of the material being analysed (MSL_m) (in order to estimate how many times that material will have to be replaced over the useful life of the building) with year 1 subtracted from it (so as not to double count the embodied energy required at year 1 as this has been included as IEE). This value is then rounded up to the nearest whole number (as materials can only be replaced in their entirety). This number is then multiplied by the quantity of the respective material (Q_m) and the embodied energy coefficient (EC_m), to estimate the embodied energy of the materials being replaced. In order to take into account the amount of materials wasted on site, a wastage coefficient (W_m) is further multiplied. The total energy requirement (TERBS) of the residential building sector has to be determined. The total energy requirement of the material being analysed (TER_m) is subtracted from the total energy requirement of the building related input-output sector (TERBS). Then, in order to ensure that no material or process is double counted, the sum of the energy requirements of all the total input-output pathways not associated with the replacement of that material is also subtracted ($NATER_m$). This value is then multiplied by the cost of the material (C_m).

Equation 3.5

$$REE_b = \sum_{m=1}^{M} \left[\left(\frac{POA}{MSL_m} - 1\right)\right] \times \left[\left(Q_{m,b} \times EC_m \times W_m\right) + \left(TERBS - TER_m - NATER_m\right) \times C_m\right]$$

Where:

REE_b =	*Recurrent embodied energy of building, GJ*
POA =	*Period of analysis, years*
MSL_m =	*Material service life of the material m, years*
Q_m =	*Quantity of material m in building b in functional unit, tonne/m/m^3/m^2*
EC_m =	*Hybrid energy coefficient of material m, GJ per functional unit*
W_m =	*Wastage coefficient of material m*
TERBS =	*Total energy requirement of building sector construction-related input-output sector n, GJ/AUD1000*
TER_m =	*Total energy requirement of the material production processes for which process data is available, GJ/ AUD1000*
$NATER_m$ =	*Total energy requirements of all input-output pathways not associated with the installation or production process of material m being replaced, GJ/ AUD1000*
C_m =	*Cost of material m, AUD*

Source: Stephan and Crawford (2015)

The following section describes the data inputs in more detail as per the variables included in Equation 3.5.

Period of analysis (POA)

This refers to the analysis period for the building assessment. This input will depend on the user and will relate to the type of building, the aim of the study and the user's expectation and assumptions. Examples of POA include Stephan and Stephan (2017) and Rauf and Crawford (2013) who used a 50 year POA.

Material service life (MSL_m)

Examples of some average material service life values, which is the replacement rate (which refers to how often a material has to be replaced), are provided in Table 3.5.

Table 3.5 Average material service life values

Material	Average service life (years)	Sources
Concrete roof tiles	40	*Ransley and Tyrrell (1998); Condor (2008)*
Bricks	Lifetime	*Seiders et al. (2007);Chapman and Izzo (2002)*
Plasterboard Water-based paint	35 10	*Ransley and Tyrrell (1998); InterNACHI (2012); Fay et al. (2000)*
Aluminium-framed windows	25	*LCCS (2001); Condor (2008); Thomas et al. (2015)*
Timber-framed windows	40	*(Ransley and Tyrrell, 1998); InterNACHI (2012); Seiders et al. (2007)*
Nylon carpet	25	*Bowyer (2009); Condor (2008)*

Refer to Section 3.2.6.1 above, for an explanation of quantity of material, embodied energy coefficient, wastage factor and total energy requirement of building sector variables used in the REE calculation.

Total energy requirement of the material being replaced (TER_m)

Refer to Table B7 in Appendix B for an example of key material related input-output pathways values. For example, the TER_m value for paint is 0.1259 GJ/AUD1000 and is based on the data provided by Crawford and Treloar (2010).

Total energy requirements of all input-output pathways not associated with the installation or production process of material m ($NATER_m$)

In order to avoid the inclusion of the embodied energy of materials and processes that are required for initial construction of the dwelling, but not required for ongoing maintenance and repair, it is necessary to subtract the energy requirement associated with those processes that are not associated with replacement of each individual material when calculating the remainder (Rauf and Crawford, 2013). This is due to the fact that only specific processes are required for replacement of individual materials (as opposed to the processes associated with initial construction of a building). For example, including the energy demand associated with ceramic products; iron and steel; wood products; textile products and glass products for example would be overestimating the energy demand associated with replacing the paint. Refer to Table B8 to Table B11 in Appendix B for an example of the values that can be used.

Cost of material (C_m)

The cost of the material can either be supplied directly by the user, if known, or can be extracted from cost guides and databases such as Rawlinsons (2017), which provides the price per square meter (m^2) of various materials.

3.4.1.3. Total embodied greenhouse gas emissions

The embodied energy values (initial and recurrent) must be converted to equivalent GHGE values with the use of an emission factor (EF). This EF is dependent on the GHG being assessed (for example CO_2, CH_4 or N_2O) and the fuel source (for example black coal, wood, natural gas or ethanol). Different fuel sources release different GHGE. The EF is a representative value that relates the quantity of a pollutant released to the atmosphere. In order to simplify this process an average EF is often used to convert embodied energy values to GHGE values. For Australian-based studies an average EF of 60 $kgCO_2e$ per GJ has often been used (Treloar et al., 2000; Crawford, 2011). Using a single average EF, as in this instance, does over simplify the reality of the actual emissions related to different materials and processes (for example concrete has higher embodied emissions than wood due to its energy intensive manufacturing process) and these limitations should be taken into account. However due to time and data constraints of this study, this average EF has been used in the framework as there is a lack of detail about where the materials come from, the production processes involved and percentage of raw material, for example, used for the case study building. The total embodied GHGE is calculated by adding the IEE and REE (which have been multiplied by the average EF) as per Equation 3.6, and is expressed in $kgCO_2e$.

$$LCEGHG_b = (IEE_b \times EF) + (REE_b \times EF) \quad \text{Equation 3.6}$$

Where:

$LCEGHG_b$ = Life cycle embodied GHG emissions of building b, $kgCO_2e$

IEE_b = Initial embodied energy of building b, GJ

REE_b = Recurrent embodied energy of building b, GJ

EF = Emission factor, $kgCO_2e$

Source: Crawford (2011)

3.4.1.4. Operational greenhouse gas emissions calculation method

This life cycle phase refers to the ‘use and operation’ stage of the building, i.e. the energy used for running the building (heating, cooling and lighting) and the consequential GHGE. It depend on a range of factors including the building type, envelope, heating and cooling systems, number of occupants and their expected activity level. Chapter 2 (see Section 2.3.2) provided an overview of the various methods available to quantify operational energy and GHGE, from steady-state equations to dynamic simulation. This chapter concluded that dynamic simulation is often the preferred method within industry and provides a more realistic energy demand prediction by virtue of the fact that it can factor in elements such as thermal mass and solar radiation (Van der Veken et al., 2004). Chapter 2 also provided a brief overview of the multiple software programmes available to carry out these dynamic simulations, such as Green Building Studio (GBS) or IES.

The operational GHGE (OGHGE) result will depend on the building and users and type of calculation method and software used. It is assumed that the user will use a dynamic simulation software program due to their popularity in the construction industry (Fouche and Crawford, 2015), therefore this approach has been selected as the preferred method of calculating OGHGE for this study.

Quantifying the delivered operational energy

Building simulation is a computational model that approximates the performance of a building in terms of either expected energy consumption, GHGE, daylight requirement; ventilation requirements or thermal comfort (AIRAH, 2015). In order to simulate the building’s expected performance, the information and data inputs, as outlined in Table 3.6, has to be provided.

Table 3.6 Example of the data input requirements for simulating building operational energy

Data requirements	Detail
Building location	Country, city and appropriate weather file.
Building geometry	Shape, size, area, volume and height
Building materials	Walls, windows, roof, floors, insulation, finishes. U-Values and shading coefficients.
General operation of the building	Number of occupants, operation of windows and hours of building operation.
Interior load values	Lighting, plug loads, internal temperature set points and activity level.
Zoning requirements	Zone and function of each space in building.
System types	Mechanical cooling system, heating system and hot water system.

Sources: AIRAH (2015), Energy Models (2013), Schwartz and Raslan (2013), Autodesk (2013), U.S DOE (2016)

Once the data has been entered into the selected simulation software, the buildings operational energy will be estimated including, for example, some of the following load estimates: energy use intensity (MJ/m^2/year); annual peak demand (kW); annual electric end use (kWh); annual fuel end use (MJ), space heating and cooling requirements (kWh); hot water (kWh); façade loads (kWh) and internal temperature range (°C) (Autodesk, 2013; AIRAH, 2015).

When interpreting the results of a simulated energy model it is important to consider that most software packages tend to apply a number of simplifications and assumptions (particularly with regard to factors such as occupancy and operational schedules, external features and adjacent buildings) (AIRAH, 2015). The level of accuracy of the model will also be directly proportional to the level of detail and information contained within the model. Studies such as Schwartz and Raslan (2013) and Fumo (2014) have also noted a possible difference in energy simulation tools of ±30% and monthly building loads of ±40%, respectively. In order to take this variability into account, it has been recommended (and has been selected to be included in this study) that a ±20% range in operational energy and GHGE results be included (Kentish and Peterson, 2009; Crawford, 2013).

Quantifying the primary operational energy

Once the user has estimated the annual delivered energy that the building is expected to use in its operation, it must be converted from delivered energy to primary energy terms. This is necessary in order to take into account the total energy contained in natural reserves of primary fossil fuels (for example coal or natural gas). Primary energy refers to the raw state and accounts for losses in extraction, conversion, transmission and distribution (Treloar, 1998). The primary energy demand is determined by multiplying the delivered energy demand by the appropriate primary energy conversion factor. The selected primary energy factors, as described in the Table 3.7, can be used for Australia.

Table 3.7 Primary energy conversion factor

Fuel	Primary energy factor
Natural gas	1.4
Electricity	3.4

Source: Treloar (1998)

Equation 3.7 was used to calculate the primary operational energy. If electricity is used as the energy source, the efficiency of the system is replaced with a coefficient of performance (COP), which is the ratio of output power divided by the input power regardless of the energy quality.

Equation 3.7

$$POE_b = \sum_{v=1}^{V} DOPE_{v,b} \; x \; PEF_v$$

Where:

POE_b = Annual primary operational energy demand of building, GJ

$DOPE_{v,b}$ = Annual delivered operational energy demand of building b for energy demand v, GJ

PEF_v = Primary energy conversion factor for energy demand v

Adapted from: Stephan (2013)

Quantifying the constrained operational energy

The energy values obtained from dynamic simulation occasionally fail to take any occupancy and zoning variability into account, therefore the values are unconstrained (Fuller and Crawford, 2011). This refers to the fact that simulation struggles to predict realistic occupant behaviours, for instance occupants may choose not to heat or cool the house all year round. Williamson et al. (2010) found that dwelling occupants express general satisfaction with indoor conditions that fluctuate with external conditions and that they do not act to maintain 'thermal comfort' within the predicted thermostat settings. This is referred to as the occupant factor. Another factor that simulation struggles to realistically model is the tendency of occupants to only condition specific parts of their house, like the living room, creating some discrepancy with the assumed zoning in the simulation tool (DEWHA, 2008; AGO, 1999). This is known as the zoning factor. Both these factors are combined to represent the constraint factor, which is multiplied by the primary energy figure in order to estimate a more realistic primary operational energy figure for a building (refer to Equation 3.8). Examples of constraint factors used in previous studies include 0.45 and 0.4 for the heating and cooling energy respectively, for Victorian dwellings (AGO, 1999; Fuller and Crawford, 2011).

Equation 3.8

$$CPOE_b = \sum_{use=1}^{USE} POE_{use,b} \times CF_{use}$$

Where:

$CPOE_b$=	Constrained primary operational energy demand of building b, GJ/year
POE_b=	Primary operational energy of building b, GJ
CF=	Constraint factor

Adapted from: Crawford et al. (2016)

Quantifying the life cycle operational greenhouse gas emissions

In order to determine the total life cycle operational GHGE (LCOGHG), the primary operational energy figure must be multiplied by an emission factor (EF) and global warming potential (GWP), as set out in Equation 3.9. This EF is dependant on the GHG being assessed (for example, CO_2, CH_4 or N_2O) and the fuel source (for example, black coal, wood, natural gas or ethanol). This factor represents the unit of equivalence based on the degree to which each input or output contributes to global warming, which is typically measured in carbon dioxide equivalents (CO_2e). Table 3.8 provides examples of EF applicable to energy use in Victoria, Australia.

$$LCOGHG_b = CPOE_{b,v} \times EF_V \times GWP_V \times POA$$ *Equation 3.9*

Where:

$LCOGHGE_b$ =	Life cycle operational greenhouse gas emissions of building, $kgCO_2e$/year
$CPOE_b$ =	Constrained Primary Operational Energy of building b based on energy demand v, GJ
EF=	Emission factor of energy demand v, kg/GJ
GWP =	Global warming potential of energy demand v, CO_2e
POA =	Period of analysis, years

Source: Crawford (2011)

Table 3.8 Global warming potential and emission factor for various greenhouse gases

Fuel	GHG	Emission factor (kg/GJ)	Global warming potential (CO_2e)
Electricity (Brown Coal)	Carbon dioxide (CO_2)	92.7	1
	Methane (CH_4)	0.00048	25
	Nitrous oxide (N_2O)	0.0013	298
Gas	Carbon dioxide (CO_2)	51.2	1
	Methane (CH_4)	0.0048	25
	Nitrous oxide (N_2O)	0.000097	298

Source: Crawford, (2011)

3.5. Select appropriate economic quantification techniques

LCC has been selected for this study for the evaluation of the economic performance of buildings (as discussed in Section 3.3.1). There are several LCC quantification approaches, as discussed in Chapter 2 (Section 2.4.2.2), including NPV, IRR and payback analysis. Payback analysis has not been selected for this study, as it does not take into account the time value of money (Berk and De Marzo, 2014). Though IRR takes the time value of money into account, it has not been selected for this study as it can often lead to misinterpretation for projects with delayed investments (Berk and De Marzo, 2014). Several energy efficient strategies have longer payback times, for example solar PV, which for Victoria has been estimated to be roughly 10 years or more (Sheftalovich, 2013). This selection of a LCC technique that can take such delayed investments into account was therefore required. The NPV approach has been selected for this study in order to quantify LCC and address the economic quantification section of research question 2 (Table 3.1). The NPV technique provides a reliable means of estimating the value of a building related investment over time (Gallo, 2014; Berk and De Marzo, 2014). This method considers the concept of time value of money with the inclusion of applicable discount rate and period of analysis. It is also widely used in environmental focussed life cycle studies such as Stephan and Stephan (2017), Ristimäki et al. (2013) and Schwartz et al. (2016).

LCC is used, similar to comparative LCA, to compare the performance of one building design option with another, but from an economic perspective. Costs have been grouped into initial costs (the costs incurred at the start of the project); replacement costs (the costs associated with replacement of building elements over the building lifetime) and operational costs (the costs associated with the running of the building, for example heating and cooling), complementing the life cycle GHG phases discussed before. Net Present Cost (NPC) is another term often used in environmental LCC studies (such as Kempton and Letendre (1997), Kusakana and Vermaak (2014) and Budischak et al. (2013)). It is similar to NPV, but it inverts the NPV value and presents it in a more relatable manner to users (i.e. a positive NPC will cost the user money and a negative NPC will save the user money). The NPC approach also presents a comprehensive means of estimating the value of a building-related investment over time (Gallo, 2014; Berk and De Marzo, 2014). To simplify interpretation of results and increase familiarity to users, NPC (instead of NPV), has been used in this study (as the user is more likely to understand a cost in terms of a positive number and a saving in terms of a negative number).

The NPC equation used in this study is based on the research presented in Chapter 2 and has been adapted from Schwartz et al. (2016) and Stephan and Stephan (2016) as set out in Equation 3.10.

Equation 3.10

Initial costs for year 0 | Replacement costs for year 0 to 50 | Operational costs for year 0 to 50

$$NPC_S = \sum_{m=1}^{M}(Q_m \times CC_m) + \sum_{y=1}^{POA} \frac{[(\sum_m(\propto_{m,y} \times Q_m \times CC_m)+(\sum_v(OE_c)]\times(1+i)^y}{(1+r)^y}$$

Condition of replacement cost for year 1 to 50

$$\propto_{m,y} = \left(0 \; if \; \frac{y}{SL_m} \neq N\right) or \left(1 \; if \; \frac{y}{SL_m} = N\right)$$

Where

NPC_b=	Net present cost of building b, AUD
$Q_{m,b}$ =	Quantity of material m in building b, unit
CC_m =	Cost coefficient of material m, AUD
POA =	Period of analysis, years
OE_c =	Operational energy cost, AUD
i=	Inflation rate
r=	Discount rate
SL_m=	Service life of material, years
N =	Set of positive integers
y =	Year

Based on: Schwartz et al. (2016) and Stephan and Stephan (2016)

The initial construction cost of a building is calculated for year 0 (as this cost does not have to be repeated again for the POA), and is calculated by multiplying the quantity of material (Q_m) multiplied by the cost of that material (CC_m). This initial cost is based on all the constituent materials ($\sum_m$) being assessed. No discount rate or inflation rate needs to be applied to this cost, as it is the present cost (i.e. not in the future).

The POA determines the number of times a material has to be replaced over the expected lifetime. The life cycle replacement cost is dependant ($\propto$) on the service life of the material (SL_m) (refer to Table 3.5) and the years at which they are replaced (y). The result has to be a positive integer (N) as an item cannot be half replaced. For example, if a design option such as paint only needs to be replaced every 10 years, its replacement cost will not be considered from year 0 to year 9 (*thus* $\frac{y}{SL_m} \neq N$). In year 10, the replacement cost of that design option will be included (*thus* $\frac{y}{SL_m} = N$).

The operational cost will be dependent on the energy demand multiplied by its cost, as described in Equation 3.11. For example if only gas (*G*) and electricity (*E*) are used, then the cost of gas (C_G) and electricity (C_E) are multiplied by the energy demand, respectively.

$$OE_c=[(G \times C_G) + (E \times C_E)] \quad \textit{Equation 3.11}$$

Where:

OE_c =	Operational energy cost, AUD
G =	Annual gas demand, GJ
C_G =	Cost of gas, AUD/GJ
E =	*Annual electricity demand, kWh*
C_E =	Cost of electricity, AUD/kWh

Based on: Stephan and Stephan (2016)

The time value of money is taken into account by multiplying the total cost (replacement and operational) by the considered inflation rate (i) and dividing it by the discount rate (r).

The next section discusses the relevant data inputs within Equation 3.10 used to calculate the LCC of a building.

Quantity of material (Q_m)

This is determined similar to the LCGHGE, (see Section 3.4.1.1)

Cost coefficient of material (CC_m)

This is a user-defined input and will be dependant on the type of material, the manufacturer and finish. If the exact cost of the material is unknown, an estimate can be extracted from a source such as Rawlinsons (2017).

Period of analysis (POA)

This is determined similar to the LCGHGE, (see Section 3.4.1.1).

Energy demand (G and E)

Four main fuel types are predominantly used in the residential sector in Australia, namely electricity, mains (natural) gas, liquefied petroleum gas (LPG) and wood. There is an increasing proportion of total residential energy demand being met by electricity and a decrease in the use of wood. There is an increase in gas and solar technologies being used to supply water heating (DEWHA, 2008). The source of energy will be user defined and dependant on the type of building and its location.

Cost of energy (C_v)

This is user defined and depends on the location of the building and the type of fuel being used.

Inflation rate (i)

This value will is user defined and will be dependant on the location of the building. For example, the inflation rate for Australia has averaged 5.15% from 1951 to 2015 (with the lowest rate recorded at -1.30% in 1962 and the highest of 23.90% in 1951) (Trading economics, 2016).

Discount rate (r)

The calculation used to determine the discount rate, based on the Capital Market Model (CAPM) as presented by Berk and De Marzo (2014), is provided below in Equation 3.12.

$$r = r_E \frac{E}{E+D} + r_D \frac{D}{E+D}(1-\tau_D)$$

Equation 3.12

Where:

r = *Discount rate*

r_E = *Cost of equity*

r_D= *Cost of debt*

E= *Project equity value*

D= *Project debt value*

τ_D= *Effective tax rate*

Source: Berk and De Marzo (2014)

To calculate the cost of equity (r_E) the following CAPM equation has been used, Equation 3.13

$$r_E = r_f + \beta(r_M - r_f)$$ *Equation 3.13*

Where:

r_E = *Cost of equity*

r_f = *Risk free rate*

r_M = *Market return*

β = *Investment risk premium compared to market*

Source: Berk and De Marzo (2014)

Service life of material (SL)

This refers to the frequency (in years) that a material must be get replaced over the POA of a building. Refer to Table 3.5

3.6. Select appropriate methods available to aid environmental and economic integration

The aim of this study requires the integration of both the environmental result and the economic result (as based on the selected calculation methods described above). In order to answer research question 3 (the selection of appropriate methods to aid this integration), the following section has been divided into three parts. The first part discusses the methods selected to integrate the environmental and economic results into a single value (in order to ensure that the results are not simply provided in isolation of each other, as is the case with most previous studies tend to do, but actually assimilated to further aid interpretation). The second part selects the appropriate methods for which to aid the integration process through visualisation of results (one of the key gaps from previous studies and frameworks). The third part selects the appropriate sensitivity analysis technique (a vital component of any life cycle based study, in order to deal with the significant level of uncertainty).

3.6.1. Select appropriate method to integrate environmental and economic results

The lack of integration of environmental and economic results is a major weakness of current life cycle studies. Most studies refer to these results separately , making it harder to understand the relationship and trade offs between these two aspects (such as Bull et al. (2014) and Gu et al. (2008)). Some studies that have attempted to integrate these two variables include Schwartz et al. (2016) and Ristimäki et al. (2013). However, though the results are illustrated, for example, in one graph, the results are not actually integrated into a single value. Results rely on more than one point being plotted or multiple axes being required.

Chapter 2 provided an overview of the methods available to assist the integration process. MCDM approach (see Section 2.6.2) has been selected for this study as it can help the decision-making process when multiple variables have to be considered (such as GHGE and cost); its applicability to environmental studies simular to this one (see Section 2.6.2.1) and the fact that the outcome is dependant on the user (as there is no single optimal solution to fit all user needs) (Ho, 2008; Jato-Espino et al., 2014; Mardani et al., 2015). This is especially helpful when a decision-support framework has to allow for user preferences, constituting a weakness in studies such as Deng et al. (2008) and Savino et al. (2017).

Another method discussed in Chapter 2 and selected for this study was the marginal abatement cost (MAC) approach (see Section 2.6.4). The MAC approach provides the results in terms of cost per tonne of GHGE abated (i.e. reduced) which is in the form of $/t$CO_2$e abatement. It has been selected as it is regularly quoted as a decision-support tool, useful for evaluating and comparing the performance between different energy efficient strategies (WALGA, 2015). It is a simple way of identifying, which project/ option being assessed, is the most cost effective per unit of CO_2e abated and which option provides the greatest abatement potential. A negative cost (-$) does not incur any extra financial cost to the user and possibly leads to financial savings, where as a positive cost (+$) incurs an additional financial cost to the user. MAC is calculated by dividing the NPV by the total GHGE abated over the life time of the built project. This technique has been used in several similar studies and publications, such as Pears (2016), Element Energy (2013) and Ibn-Mohammed et al. (2013). Due to its applicability to this study's research focus and its ability to help evaluate and compare built projects, the MAC approach has been selected to help integrate the environmental and economic results into a single value. However, when using this technique it is important to be aware of some of the possible drawbacks of

MAC. It focuses only on the direct costs; is dependant on the quality and reliability of data and is limited to the objectives of the study, to name but a few (Ibn-Mohammed et al., 2013).

3.6.2. Select visual output methods for results

A key gap from the previous studies is that most of them did not provide any form of visual output for the integrated environmental and economic results (Bierer et al., 2015; Heijungs et al., 2013; Hoogmartens et al., 2014; Petrillo et al., 2016). As stated before in Chapter 2, many people have difficulty in interpreting numbers and tables and providing a form of visual output can potentially ease the understanding of the results and better demonstrate trade-offs and relationships between variables (Baez et al., 2012). Chapter 2 provided an overview of the various visual outputs that can be used to visualise environmental and economic results ranging from the network theory (graph theory) approach (see Section 2.6.3), to the four-quadrant approach (Figure 2.5) and the MACC approach (see Section 2.6.2).

Some of the studies that managed to integrate environmental and financial data into a single graph make use of scatter plot graphs, such as Huppes and Ishikawa (2005), Langston and Langston (2008), Savino et al. (2017), Stephan and Athanassiadis (2017) and Schwartz et al. (2016). Scatter plots, that fall within the graph theory approach, are useful in the illustration of the relationship between two sets of quantitative data for the same object. The y-axis will relate to the one set of data and the x-axis to the other. A dot is then made where the two sets of data meet each other for that specific object. Scatter plots are useful in illustrating large amounts of data and are relatively easy to interpret. These types of graphs can also help emphasise correlation, but correlation should be based on a large and statistically relevant sample size (Manly and Alberto, 2017). As this study's framework must be able to demonstrate the relationship between these variables (i.e. environmental and economic), scatter plot was deemed appropriate and accordingly selected. This framework's integrated output must address the weakness of the visual output of the previous studies, for example not providing a relatable functional unit, unlike Schwartz et al. (2016), not applying any weighting or scaling factors, unlike Savino et al. (2017) and it must provide results based on all life cycle stages, unlike Langston and Langston (2008).

A technique that further compliments this scatter plot approach, and has been selected for this study, is the four-quadrant approach used in studies such as Torcellini et al. (2014), as illustrated in Figure 3.6 (and discussed in Section 2.6.3).

The relationship between two sets of data is still presented in the form of a scatter plot (the investigated design options appear as dots in each quadrant based on their results). It has been selected due to its applicability to multiple criteria and the fact that it can help demonstrate and visualise trade-offs and relationships. The final interpretation of the combined results will depend on the quadrant within which the building design option falls. If the option falls within quadrant 3, the option decreases the LCGHGE of the building, when compared against the base case, and results in a decrease in net cost, thus presenting quite a favourable outcome. However, if a design option falls within quadrant 1, for example, the design option performs worse than the base case on both a GHGE and financial level and may not be a preferred design option.

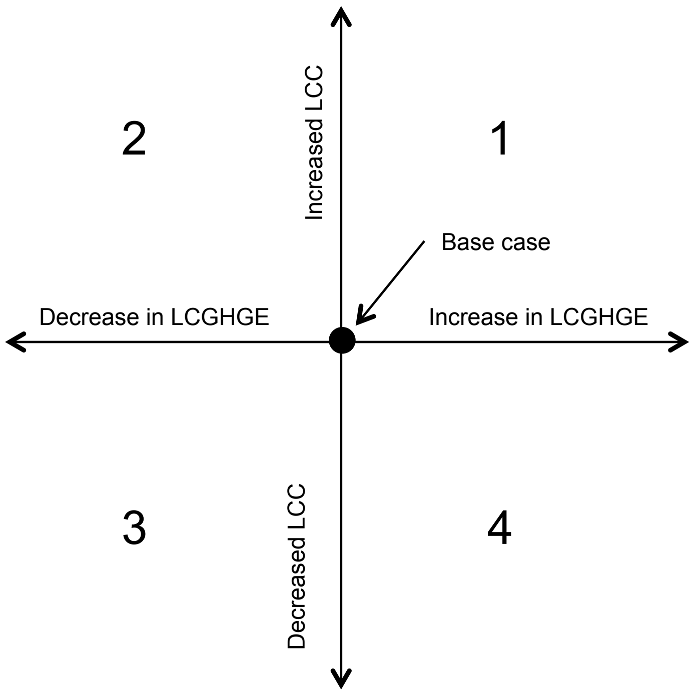


Figure 3.6 Four-quadrant approach demonstrating the decision trade-off graphical framework

Based on Torcellini et al. (2014)

Column or bar charts are one of the most common visual outputs used in previous studies (as discussed in Section 2.6.3) to illustrate either the environmental or economic results and have been selected for this study. These types of charts provide a visual comparison, for example the LCGHGE comparison between 2 or more building design options, and thus applicable to this study's research focus. For bar charts, the y-axis has a scale (usually starting at 0 and increasing or decreasing in value) and the x-axis represents the different categories (such as the building options being assessed), as illustrated in Figure 3.7. The numerical value is based on one value, for example the mean, and error bars should be employed to show any uncertainty pertaining the data (discussed in more detail below in Section 3.2.10). This is especially helpful with embodied GHGE results, which, as discussed before, has an uncertainty range of about 40% (Crawford, 2013). Examples of studies that have used this technique include Brown et al. (2014) and De Wolf et al. (2015) and an example is illustrated in Figure 3.7 and Figure 3.8 for a hypothetical LCGHGE and LCC result.

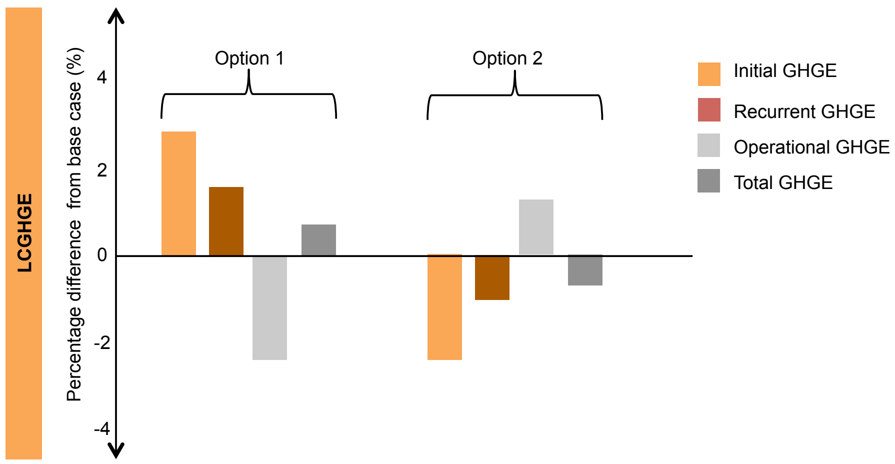


Figure 3.7 Example of bar chart used to illustrate life cycle greenhouse gas emissions results, by life cycle stage

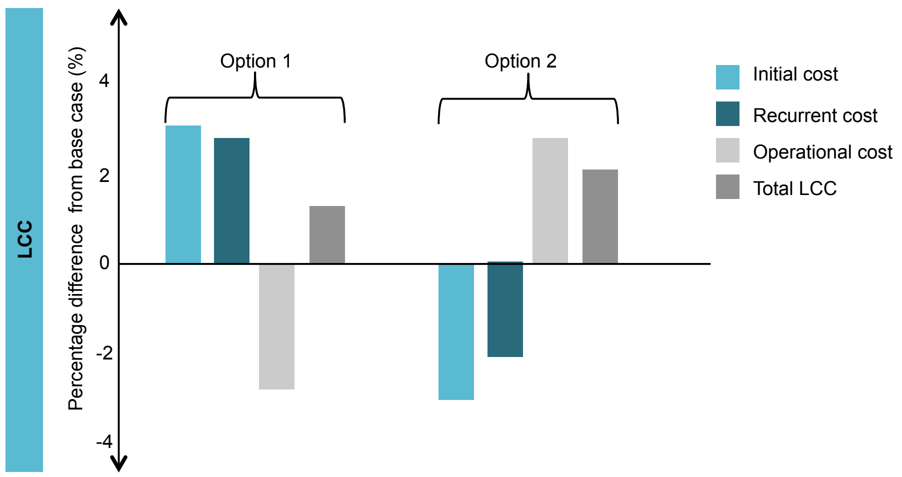


Figure 3.8 Example of bar chart used to illustrate life cycle cost results per life cycle stage

The visual outputs discussed above (i.e. scatter plots and column charts) effectively demonstrate relationships and comparisons, particularly for more than one variable. As this study's framework, and selected approaches such as MCDM, addresses the need to illustrate trade-offs and the relationships between multiple criteria (namely GHGE and cost in this study), these types of graphs have been deemed most appropriate and accordingly have been selected. Examples of these visual outputs have been provided in Chapter 5 which demonstrate the potential of the framework.

Graphs that are not ideal for demonstrating these key requirements include a line graphs (which are more ideal for continuous data sets over a period of time) and pie charts (which are more ideal for static information and not recommended for data visualisation as most people struggle to interpret angles and areas) (Gulbis, 2016). In consequence, these types of visual outputs have not been included in this study.

3.6.3. Select sensitivity analyses techniques

As discussed in Chapter 2 (see Section 2.3.6.1 and 2.4.2.4), life cycle studies are subject to a large degree of uncertainty. Uncertainty relates to the lack or absence of knowledge regarding certain parameters (Heijungs and Huijbregts, 2004). A significant proportion of the uncertainty stems from the input values selected, the knowledge of the assessor, the scope of the assessment, the reliability of the data and the objectivity of the approach to the final selection, to name but a few (Babashamsi et al., 2016; Gluch and Baumann, 2004; Dixit et al., 2012a). In order to take into account this uncertainty a sensitivity analyses must be conducted and it constitutes an essential part of the final interpretation (Groen et al., 2014). There is no legislation requiring this sensitivity analysis, but several studies include it as part of their building evaluations to test the reliability of their results (Stephan and Stephan, 2016; Leckner and Zmeureanu, 2011; Rauf, 2015).

Several methods are available to assess the sensitivity of results (as summarised in Chapter 2, Table 2.2). Some methods, such as Monte Carlo and Sobol, require copious amounts of data and are quite time consuming. This study's research aim is aimed at the typical data available at an early stage of the design, requiring a sensitivity analysis method more suited to low-level data is required, such as OAT and scenario analysis. OAT, where each sensitivity parameter is adjusted individually in order to observe the influence it has on the final result, is easy to preform and understand (Groen et al., 2014) and is suited to the type of data usually available at an early design stage. Method of elementary effects (MEE), which can be regarded as an extension of OAT (de Koning et al., 2010), is also in such early stage analysis, where a range of values (with an upper and lower boundaries) can be tested. For the reasons aforesaid, OAT and MEE have been selected for this study's sensitivity analysis.

Sensitivity analysis often employ of the term 'sensitivity parameter' which is a parameter of a change that considerably influences the results or that contributes to the variance of the output (Groen et al., 2014). Table 3.9 below provides the sensitivity parameters most frequently included in environmental and economic life cycle studies (as discussed in Chapter 2) and have been selected for this study.

Table 3.9 Sensitivity parameters selected for this study

Sensitivity parameter	Variation/ Scenario
DR and IR (1,2,3,4,5,6,7)	Low DR, Low IR
	High DR, High IR
POA (1,2,3,5,10)	Low POA
	High POA
MSL (3,11)	Min MSL
	Max MSL
GHGE variability (8,9,10,12)	Min GHGE
	Max GHGE

Abbreviations: DR: Discount Rate, IR: Inflation rate, POA: Period of analysis, MSL: Material service life, GHGE: Greenhouse gas emissions, OGHGE: Operational greenhouse gas emissions, Min: Minimum, Max: Maximum
Sources: [1]*Stephan and Stephan (2016)* [2]*Leckner and Zmeureanu (2011)* [3]*Flanagan et al. (1989)* [4]*Langston (2005)* [5]*Mithraratne et al. (2007)* [6]*Ristimäki et al. (2013)* [6]*Morrissey and Horne (2011)* [7]*Islam et al. (2015b)* [8]*Crawford (2013)* [9]*Juodis et al. (2009)* [10]*Crawford (2011)* [11]*Rauf and Crawford (2013)*[12]*Petersen (1994)*

Chapter 2 (see Section 2.3.6.1) also provides an overview of various visual aids that can be used to illustrate uncertainty in results (see Figure 2.6). Due to the popularity of error bars (and the greater potential for successful user interpretation) and applicability of their use in life cycle studies (such as Stephan and Stephan (2016)), this visual sensitivity method (along with the complementary shaded approach for scatter plots) has been selected for this study for the illustration of uncertainty. Another popular method, Tornado diagrams, has been selected to present the upper and lower ranges of the results (thus suitable for MCDM and MEE analysis) and it is suitable to OAT analysis (as a single variable can be changed at a time and illustrated on the diagram).

3.6.4. Summary

This chapter provided an overview of the research methods discussed in Chapter 2 and selected in Chapter 3, to address this study's research questions, as summarised in Table 3.10.

Table 3.10 Research questions and summary of selected research methods discussed in Chapter 3

	Research questions	Research methods selected	Section
1	What are the most appropriate decision-support approaches to aid environmental and economic building related decisions?	• LCA framework for environmental building evaluation • LCC for economic building evaluation • MCDM for integrated environmental and economic building evaluation	3.3
2	What are the most appropriate environmental and economic performance quantification techniques?	• Path Exchange hybrid for initial and recurrent embodied environmental quantification • Dynamic for operational environmental quantification • NPV for life cycle economic quantification	3.4 and 3.5
3	How can the environmental and economic performance of buildings be integrated into a single framework for comprehensive building evaluation?	• MAC for integrated environmental and economic results • Scatter plot for visualising integrated environmental and economic results • Column and bar char for visualising separate environmental and economic results • OAT and MEE approach for sensitivity analysis of integrated results • Shaded scatter plot and tornado diagram for visualising uncertainty of results	3.6

The methods selected in this chapter form the basis of this study's developed framework for the integration of environmental and economic analyses for buildings, as discussed in the next chapter, which also provides more detail as to how research question 3 was further addressed.

4.

Developing a framework for integrating life cycle environmental and economic assessment of buildings

4.1. Introduction

The previous chapter provided an overview of the research methods selected to address this study's research aim and research questions. Chapter 3 referred to existing frameworks (such as LCA, LCC and MCDM), quantification techniques and sensitivity analyses techniques. This chapter provides further detail on research question 3, which was how can the environmental and economic performance of buildings can be integrated into a single framework for comprehensive building evaluation, was addressed. This chapter sets about developing this study's integrated environmental and economic framework. Essentially, this study's framework was developed by combining the various aspects described in the previous chapter, as illustrated in Figure 4.1.

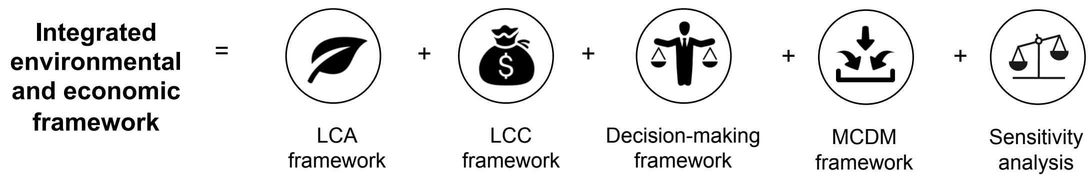


Figure 4.1 Components of this study's environmental and economic framework

This chapter describes the development of the integrated framework, listing the various tasks involved in this development, followed by defining the key requirements of the framework, approach and input parameters of the framework. Thereafter, the quantification techniques (as selected in the previous chapter) are validated by applying them to a case study building and comparing the results to other similar studies in order to ensure that the framework provides reliable results.

4.2. Framework development tasks

The development of the framework necessitated the following four tasks:

1. Define key requirements of framework
2. Define framework approach
3. Define input parameters
4. Validate selected quantification techniques

The aforesaid tasks are discussed in greater detail here under.

4.2.1. Define key requirements of framework

The key requirements of the framework, based on the gaps of previous studies (Table 2.7), include the following components:

- The integration of environmental and economic evaluation into one comprehensive single assessment (most previous studies and frameworks provide the evaluations separately).
- The evaluation of all life cycle stages (some previous studies do not explicitly include a holistic environmental or economic life cycle assessment).
- The applicability to building scale evaluation (some previous studies' frameworks and methods were only applicable to individual products or building materials and not to the whole building).
- The applicability to early stage design (some previous studies relied too much on data usually only available at a later stage in the building design process).
- The visual integration of the results (most previous studies did not provide results in an integrated manner, lacking any visual output).
- The allowance of the final selection of results to be based on the user's personal preferences (most previous studies provided final results based on predetermined selection parameters, not allowing for flexibility of the user's personal needs).

4.2.2. Define framework approach

The next task in the development of the framework was the definition of the approach (i.e. a step by step guide to the application and use this study's integrated environmental and economic evaluation method). The frameworks and methods that have been selected for study, as discussed in the previous chapter, include LCA, LCC, Decision-making (DM) and MCDM. Figure 4.2 provides a summary of these selected frameworks and includes their key steps (refer to Chapter 3 for a more detailed description of individual frameworks).

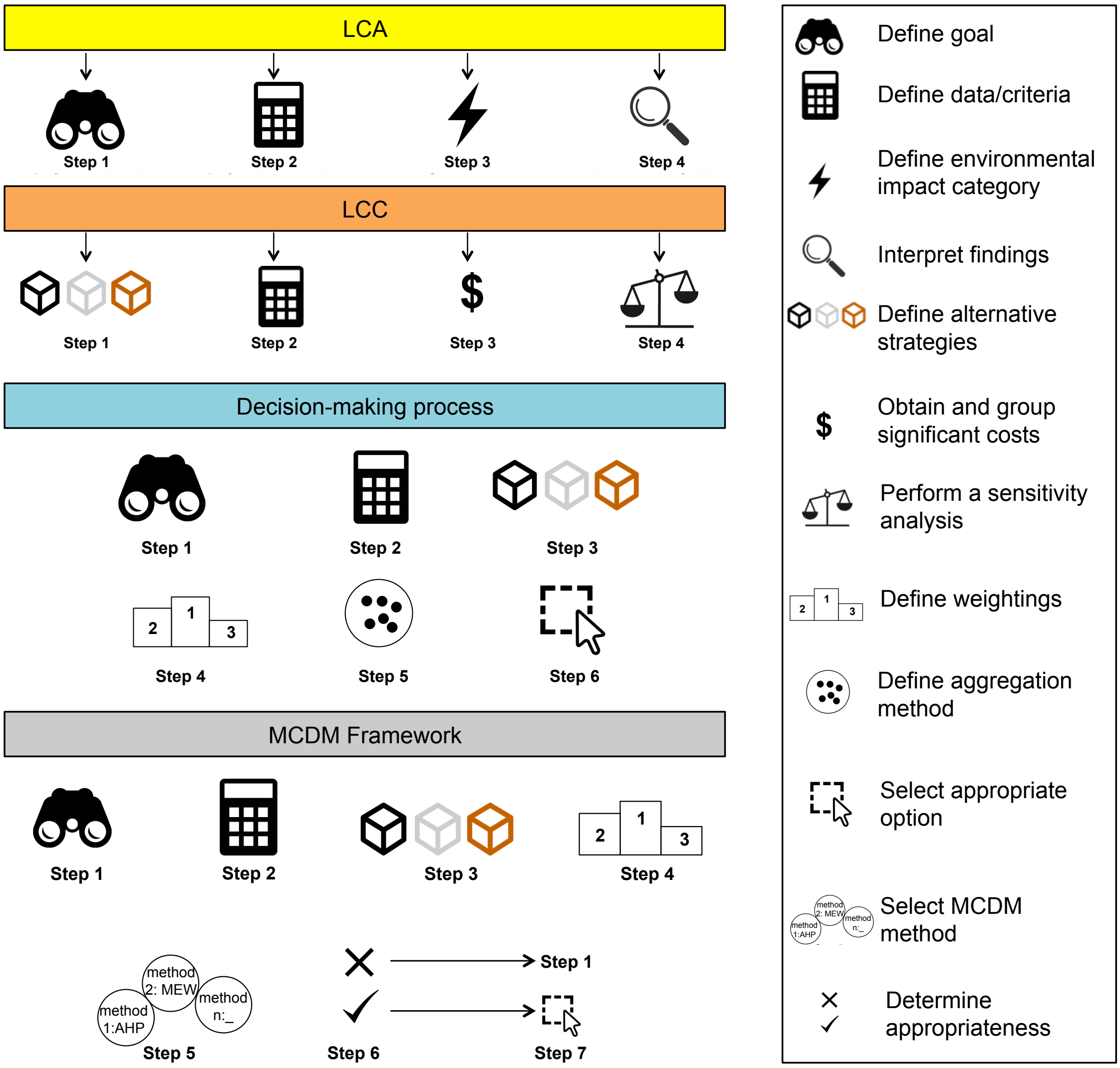


Figure 4.2 Research design outline, based on LCA, LCC, DM and MCDM frameworks (with key steps of each framework)

The individual steps from each framework were integrated to create the approach that forms part of this study's framework, as depicted in Figure 4.3. Included in Figure 4.3 is a diagram of the 9 steps, the sequence of their application and reference to their origin (i.e. from the previous frameworks as detailed by the colour coded legend). Each step is described in detail below.

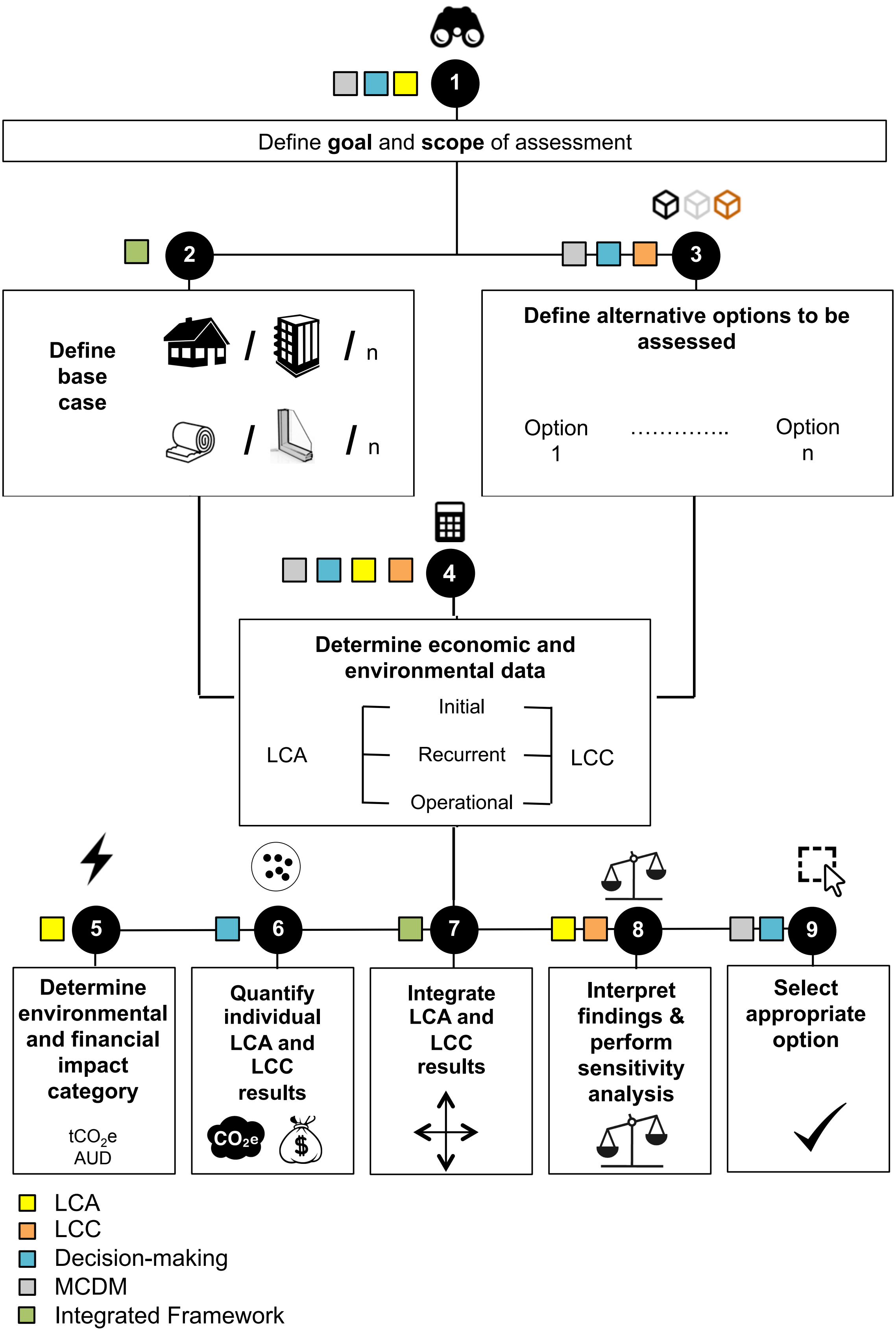


Figure 4.3 Environmental and economic framework integrated approach

4.2.2.1. Step 1: Define the goal and scope of the assessment

Step 1, which is similar to the first step of LCA, MCDM and DM, is to define the goal, scope and aim of the assessment. This step is critical as it determines the objectives of the study. The scope determines which life cycle stages that are to be considered. An example of this step would be to determine the glazing option for a residential building, which has the least life cycle GHGE and includes both embodied and operational life cycle stages.

4.2.2.2. Step 2: Define the base case scenario

The next step is to establish the base case (BC or business as usual) option against which other design options can be established. The need for this will depend on the goal of the study. The use of a BC is quite popular in LCA studies (Rauf and Crawford, 2013; Afshari et al., 2014), LCC studies (Leckner, 2008; Ristimäki et al., 2013), energy simulation studies (Beyond Zero Emissions, 2013) and energy efficiency studies (Sjølie et al., 2010; Stephan et al., 2013; Kats, 2003). The BC can be in the form of a building, an energy efficient strategy or a material, for example. It provides a point of comparison when assessing other (often multiple) strategies and can be used as a threshold to determine whether the assessed strategies perform better or worse than the base case must be considered. However, attention should be paid to the possible drawbacks of using a base case. For example, it determines the benchmark that all the consequential assessments are compared to and the sensitivity of this should be tested (Fabriek, 2013).

4.2.2.3. Step 3: Define alternative options to be assessed

Step 3 is similar to LCC's first step and DM and MCDM's third step, which is to define the alternative design/building/product options that are to be assessed in the study. These options depend on the BC and its performance. These options are compared against the BC to determine whether they perform better or worse (as determined by the objective of the study). Examples of this step include Bull et al. (2014) who assessed alternative external wall types for their energy efficient school refurbishment from a life cycle perspective, and Leckner (2008) who assessed alternative glazing options for their LCA and LCC analysis of a net zero house. The outcome of this step will be limited to the number of strategies that are included in the study (Buchert et al., 2015).

4.2.2.4. Step 4: Determine the economic and environmental data

Step 4, which draws upon Step 2 of the LCA, LCC, DM and MCDM frameworks, determines the economic and environmental data required for the assessment. This section relates to Chapter 3's selected calculations. These data elements, which are required to complete the calculations, can be referred to as input parameters and can be broadly classified as pre-defined (i.e. remains a constant parameter and does not change, regardless of assessment type) and user defined (i.e. dependant on the user, the type of project, and the location, changing with each assessment). These input parameters have been discussed in greater detail in Section 4.2.3.

4.2.2.5. Step 5: Determine environmental and economic impact category

Step 5 (similar to LCA step 3) requires the selection of an environmental and economic impact category, such as selecting GHGE (in comparison to energy or water, for example) for the LCA and AUD (in comparison to another currency, for example) for LCC.

4.2.2.6. Step 6: Quantify individual LCA and LCC results

This step draws upon Step 4 and 5 from the DM framework, where the methods for quantifying LCA and LCC are applied in order to generate results. Most studies provide LCA and LCC results separately first so that an additional layer of detail (regarding the respective environmental and economic performance) is available to the user (Anastaselos et al., 2011; Gu et al., 2008; Kneifel, 2010). However, most of these studies fail to move to the next step, which is the integration of the results.

4.2.2.7. Step 7: Integrate LCA and LCC results

Step 7, which is the critical step missing from most of the previous studies (Anastaselos et al., 2011; Bull et al., 2014; Gu et al., 2008; Kneifel, 2010; Menzies, 2010), requires the LCA and LCC results to be integrated. This step is vital for the demonstration of the relationship between the two results and their associated trade-offs. This step has been achieved through the various methods, as discussed in Chapter 3 (see Section 3.6). This includes the combination of the LCA and LCC results into a single value, as in the MAC approach (which divides the NPV result by the amount of GHGE abated). Another form of integration is aided by the visualisation of results. This is achieved through the use of scatter plots and the four-quadrant approach (see Figure 3.6), which plots the integrated LCA and LCC value in a single graphical output. This helps to counteract the gap of previous studies, which tended to provide results either in a separate format or no visual format at all.

An additional level of detail is provided with the use of bar and column charts which breaks down the LCA and LCC results per life cycle stage (see Figure 3.7).

4.2.2.8. Step 8: Interpret findings and perform sensitivity analysis

The sensitivity analysis, which is similar to Step 4 of LCC, is a vital component of any life cycle study (as life cycle studies have a significant level of uncertainty). Chapter 3 (see Section 3.6.3) selected the OAT and MEE approach for this step. One variable and one scenario at a time are tested in order to understand the effect on the final results. This will highlight possible areas of concern relating to the data and assumptions used in the evaluation and the probable reliability of the final results.

Interpreting the final results is similar to step 4 of LCA and Step 6 of MCDM, where the results have to be evaluated against the original aim of the study and determined if there is an acceptable outcome. If the outcome is acceptable, the user can move onto the next step. If not, the user will have to return to Step 1 and refine the aim and determine alternative strategies, similar to the iterative approach of MCDM (Kumar et al., 2017).

4.2.2.9. Step 9: Select appropriate option

This is the final step in the assessment and is similar to the last step in LCC, DM and MCDM. If the assessment has provided acceptable results in line with the original aim of the study, an optimal option (as defined by the user) can be selected and implemented into the final building design. This final option can be very subjective due to the decision-makers own judgement and priorities and will be limited by the knowledge of the user and the scope, criteria and level of detail of the assessment (Diakaki and Grigoroudis, 2008; Kumar et al., 2017; Buchert et al., 2015).

4.2.3. Define input parameters

The previous chapter described the various quantification methods to be used within this study's framework. These quantification methods form an integral part of Step 4 of the framework's approach, (determine data), and is a prerequisite of proceeding to Step 6 and 7 which requires the quantification and integration of the results. Each calculation requires a certain amount of data in order to perform either the LCA or LCC evaluation. This data relates to the key parameters and are essential to the makeup of the framework (i.e. the actual nuts and bolts of the framework without which there would be no results). These parameters are divided into two categories, being user defined parameters and pre-defined parameters, as stated earlier. User defined parameters refer to the type of data that would usually change in relation to the user and the building being assessed. The data will thus be building/project specific. Examples of such data include the size of the building, type of materials to be used and period of analysis. Other variable data, for example, price of goods, price of electricity and discount rate assumed, are also included in this category as this is depends on the supplier selected, the year of the available data and the location and context of the building. Pre-defined inputs refer to data that will not change for different users or buildings. This type of data remains constant for any project and does not require manually entered variables. Examples of such data include the material embodied energy coefficients, primary energy conversion factors and emission factors. It must be noted that for this study the data is based on Australian conditions and will need to be changed for building projects located in other countries. The user can manually override all data if specific data relating to their project is available. Table 4.1 provides a summary of the key input parameters included in the framework. Each input has been colour-coded and reference made (by a cross) to the life cycle stage (and relevant calculation) where each input is required.

Table 4.1 Key parameters of the environmental and economic framework

	Detail	**Life cycle stage**		
		Initial	**Recurrent**	**Operational**
User defined	Building size (m^2)	x	x	x
	Period of analysis (years)	-	x	x
	Material type	x	x	x
	Material quantity (m^2/m^3)	x	x	x
	Cost of material (AUD)	x	x	-
	Cost of building (AUD)	x	x	-
	Annual fuel source demand (GJ)	-	-	x
	Cost of fuel source demand (AUD)	-	-	x
	Sum of total energy requirements of all materials in building (GJ/AUD1000)	x	-	-
	Discount rate	-	x	x
	Interest rate	-	x	x
Pre-defined inputs	Global warming potential	-	-	x
	Emission factor	x	x	x
	Primary energy conversion factor	-	-	x
	Constraint factor	-	-	x
	Replacement rate of material (years)	-	x	-
	Material wastage coefficient	x	x	-
	Material embodied energy coefficient (GJ/unit)	x	x	-
	Building cost index	x	x	-
	Total energy requirement of building sector (GJ/AUD1000)	x	x	-
	Total energy requirement of material (GJ/AUD1000)	x	x	-
	Total energy requirement of all IO pathways not associated with the installation or production process of each material (GJ/AUD1000)	-	x	-

Appendix B (Table B1 to Table B11) sets out the pre-defined input parameters used in this study. Chapter 5 provides an example of some user defined input parameters (refer to Appendix C for more detail).

Figure 4.4 provides an example of the type of data inputs required for the quantification of LCGHGE, Figure 4.5 and the data inputs for LCC. Examples of typical data inputs (either user-defined or pre-defined) are provided along with the expected output categories and visuals.

Data type	Data input
Building type	Residential/ Commercial/ etc.
Period of analysis *(yrs.)*	20 yrs./ 50 yrs./ etc.
Area of building *(m^2)*	150 m^2 / 15000 m^2 / etc.
Material type	Concrete / timber/ etc.
Material quantities *(m^2/m^3/t)*	50 m^2 / 5 t / etc.
Embodied energy coefficient *(GJ/unit)*	4.44 / 85.46 / etc.
Wastage multiplier *(%)*	1.1 / 1.05 / etc.
Replacement rate of material *(yrs.)*	10 yrs. / 20 yrs. / etc.
Cost of material *(AUD)*	6.4 AUD/ 9.29 AUD/ etc.
Cost of building *(AUD)*	500 AUD/ 900 AUD/ etc.
Total energy requirement of building sector *(GJ/AUD1000)*	10.633 GJ/AUD1000 / 9.979 GJ/AUD1000/ etc.
Total energy requirement of material *(GJ/AUD1000)*	0.990 GJ/AUD1000/ 0.206 GJ/AUD1000/ etc.
Total energy requirement of all input-output pathways not associated with installation of each material *(GJ/AUD1000)*	3.583 GJ/AUD1000 / 4.494 GJ/ AUD1000
Annual fuel source demand *(GJ)*	45 GJ / 98 GJ etc.
Cost of fuel source demand *(AUD)*	2.43 cents / MJ / etc.
Global warming potential	1 / 25/ etc.
Emission factor	60 / 92.7/ etc.
Primary energy conversion factor	3.40 / 1.40/ etc.
Constraint factor	0.45/ 0.4/ etc.

(orange)	User-defined input
(green)	Pre-defined input
(grey)	Result

Output	Result (tCO_2e)
Initial embodied GHGE	
Recurrent embodied GHGE	
Operational GHGE	
Life cycle GHGE	

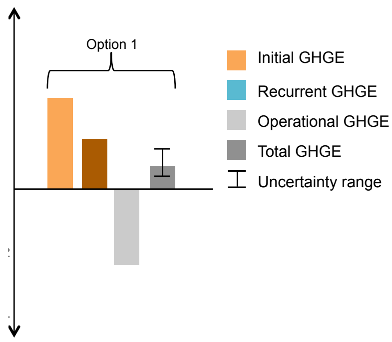


Figure 4.4 Example of the data inputs for the quantification of life cycle greenhouse gas emissions

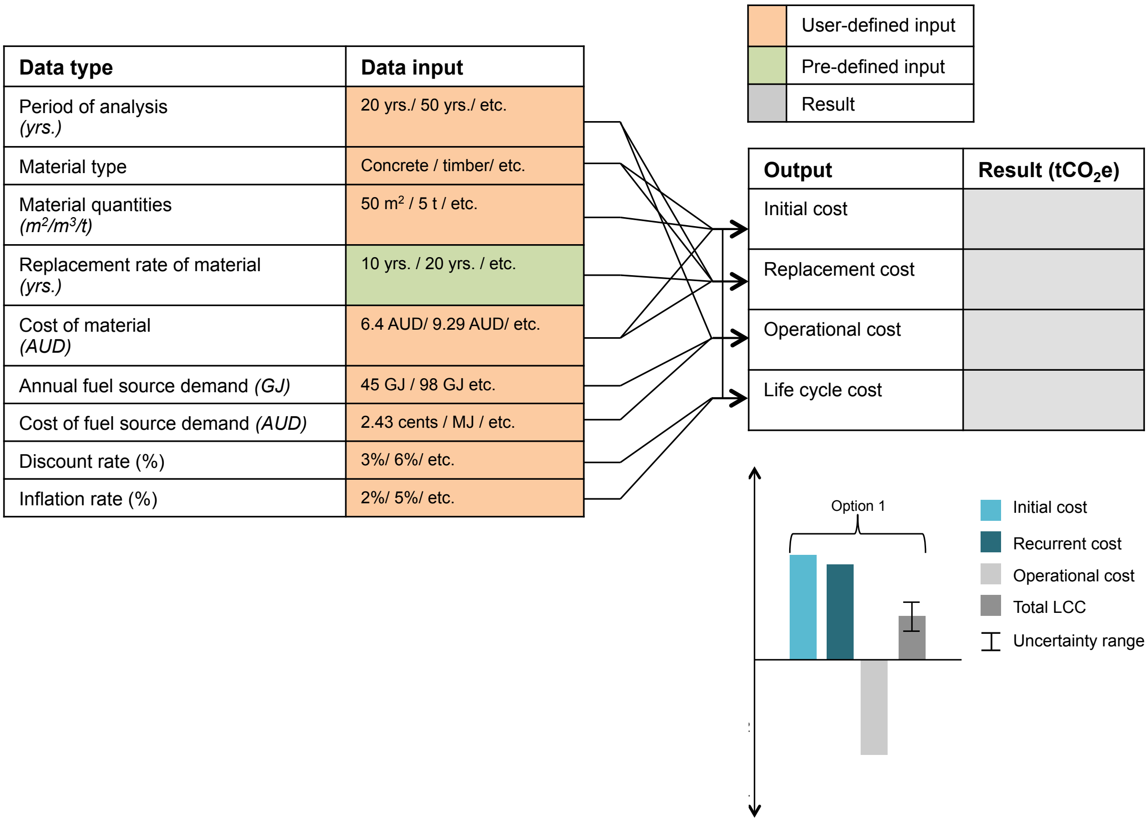


Figure 4.5 Example of the data inputs for the quantification of life cycle cost

4.2.4. Validation of quantification techniques application

The quantification techniques selected in Chapter 3 have been applied to a case study building to verify that their application provides reliable and comparable results. Providing a form of validation of methods and results has been done in similar studies such as Stephan (2013), Crawford (2008) and Williamson and Erell (2001), where one study is compared against another and aspects such as relative difference between results are checked and comparative analysis is carried out.

The use of case studies is popular in life cycle energy and GHGE studies, for example Bull et al. (2014) and Schwartz et al. (2016). Case study research enables the user to investigate and analyse a building within a specific context and isolates specific variables related to the study focus (Zainal, 2007; Gagnon, 2010). This approach narrows the scope of the research, which benefits a time consuming and data sensitive study of this nature. By selecting a case study that is representative of the widest possible range of buildings, the results can find more universal application. However, the potential disadvantages of this approach must be considered, including the fact that the results will be dependant on the type and number of case studies included (Yin, 1994; Tellis, 1997).

A Melbourne based detached residential case study dwelling is used for this study's framework quantification method validation and has been explained in greater detail in Section 4.2.4.1. Table 4.2 sets out a list of the studies used in this validation.

Table 4.2 Studies used for validation of quantification technique application

Sources	Detail
This study	230m^2 4-bedroom brick veneer detached dwelling.
Crawford (2013)	307.7m^2 4-bedroom brick veneer detached dwelling.
Fay et al. (2000)	128m^2 two-storey brick veneer detached dwelling.
Stephan (2013)	297m^2 4-bedroom brick veneer detached dwelling
DEWHA (2008)	229m^2 (number of rooms unknown) brick veneer detached dwelling
Beyond Zero Emissions (2013)	165m^2 3-bedroom brick veneer detached dwelling
Ren et al. (2013)	241m^2 4-bedroom brick veneer detached dwelling

Only the LCGHGE results are validated in this section, and include the initial, recurrent and operational GHGE results. The validation and comparison of the LCC results is discussed further in the next chapter, where the NPV technique is applied to different building elements (such as glazing and insulation) and the results then compared to similar studies. This is a result of the fact that the LCC of the whole case study building has not been quantified as part of this study, as it falls outside the scope, data availability and time constraints associated with this study. The LCC of only the building elements being assessed (and their impact on the whole buildings operational costs), as described in the next chapter, has been quantified and compared. This method of quantifying only the NPV of separate building elements only (instead of the whole building) is similar to other studies such as Stephan and Stephan (2016), who quantified the NPV of different residential energy efficient solutions such as LED lighting and PV, and Ristimäki et al. (2013), who quantified the NPV of different residential district energy systems.

4.2.4.1. Case study dwelling description

The selection process for the case study building included the following criteria. Firstly, the case study building had to represent a typical Australian residential dwelling to ensure that the case study results are generalizable and applicable to as broad a number of buildings as possible. Residential buildings alone accounted for 11% of Australia's total GHGE in 2014, which represents an increase of 43% since 1990 and 3.5% since 2013 (Australian Government: Department of the Environment, 2015). A detached residential dwelling has been selected as the case study building due to the fact that almost 80% of Australian people live in them (Australian Bureau of Statistics, 2012). In Australia, an increasing population (approximately 400,000 people a year) will result in a demand for an estimated 5.4 million additional dwellings over the next 30 years, which equates to 180,000 dwellings per annum (Property Council of Australia, 2015; Krockenberger, 2015). There is an urgent need to ensure that the typical residential buildings being built aim to reduce GHGE as much as possible.

Housing demand, coupled with rising land prices around city centres, has resulted in a significant portion of new dwellings being built in suburbs on the city fringes (Robb and Lucas, 2016). There has been a continued strong demand for detached dwellings in these suburbs (Robb and Lucas, 2016) with an increasing number of these dwellings being built by volume builders (Smith, 2016). Volume builders offer house and land packages where the buyer selects a block of land and then chooses from a number of standard home designs. These “off the plan” dwellings are often seen as “cost effective” as dwellings generally cost less per square meters than custom designed homes as savings result from mechanisms such as faster construction times, bulk buying of materials and standardised features and finishes (Smith, 2016; Robb and Lucas, 2016).

For this study, a standard 4-bedroom brick veneer design from one of the largest volume builders in Australia, Metricon, has been used. The software program Revit (Autodesk, 2016) was used to create a model of the case study building based on the information provided by Metricon (Metricon, 2017). The model includes all building elements relating to the building fabric (walls, roof, windows, doors, ground floor) and finishes (wall, ceiling and floor finish). Items that have not been included are plumbing fittings and furniture due to the fact that this can vary between houses due to homeowner preferences. It is assumed that three people live in the dwelling based on the average household size (Australian Bureau of Statistics, 2015). Figure 4.6 provides a 3D render of the building extracted from Revit. Figure 4.7 is the ground floor layout with a red line indicating the extent of the external wall insulation (the garage is not insulated). A typical section through the building is illustrated in Figure 4.8.

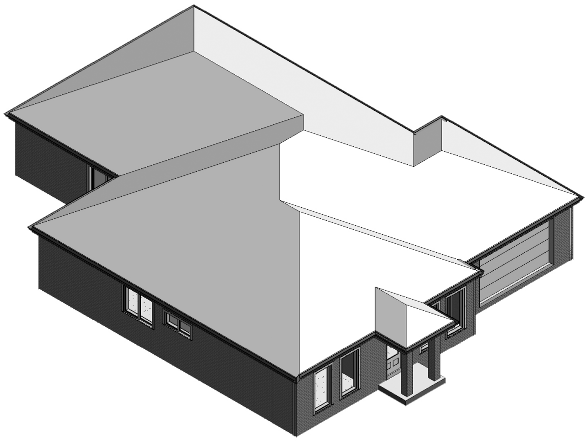


Figure 4.6 Render of residential case study building

Source based on: Metricon (2016)

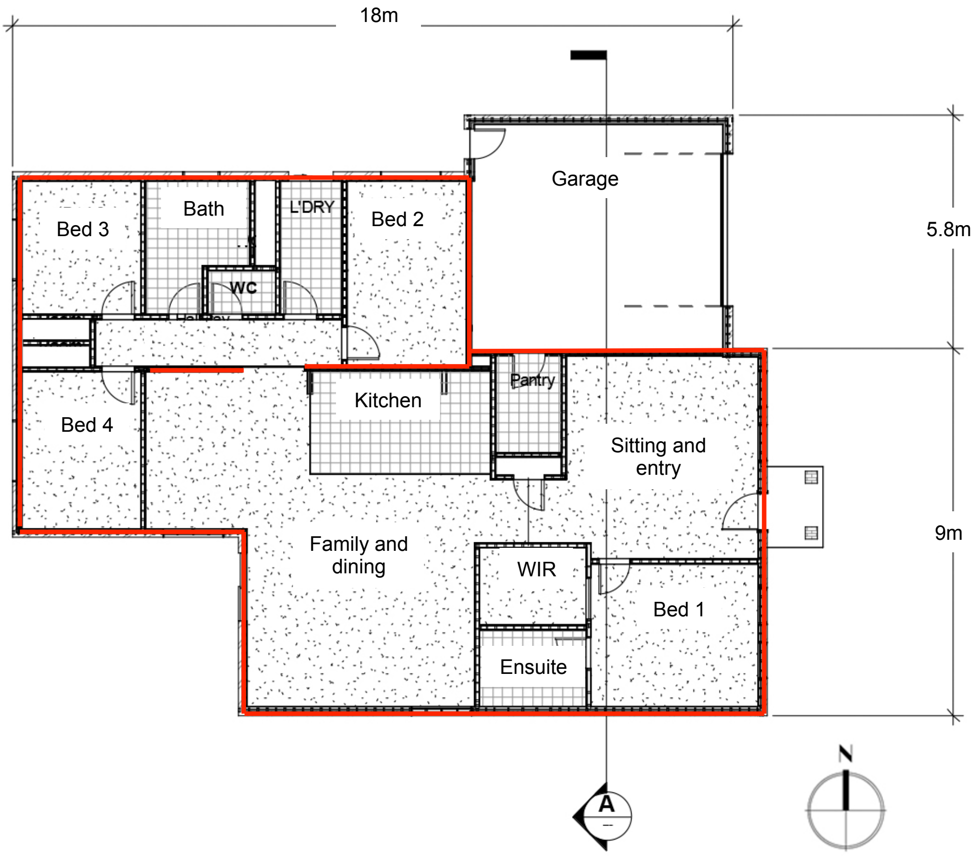


Figure 4.7 Plan of case study building with external wall insulation boundary highlighted in red

Source based on: Metricon (2016)

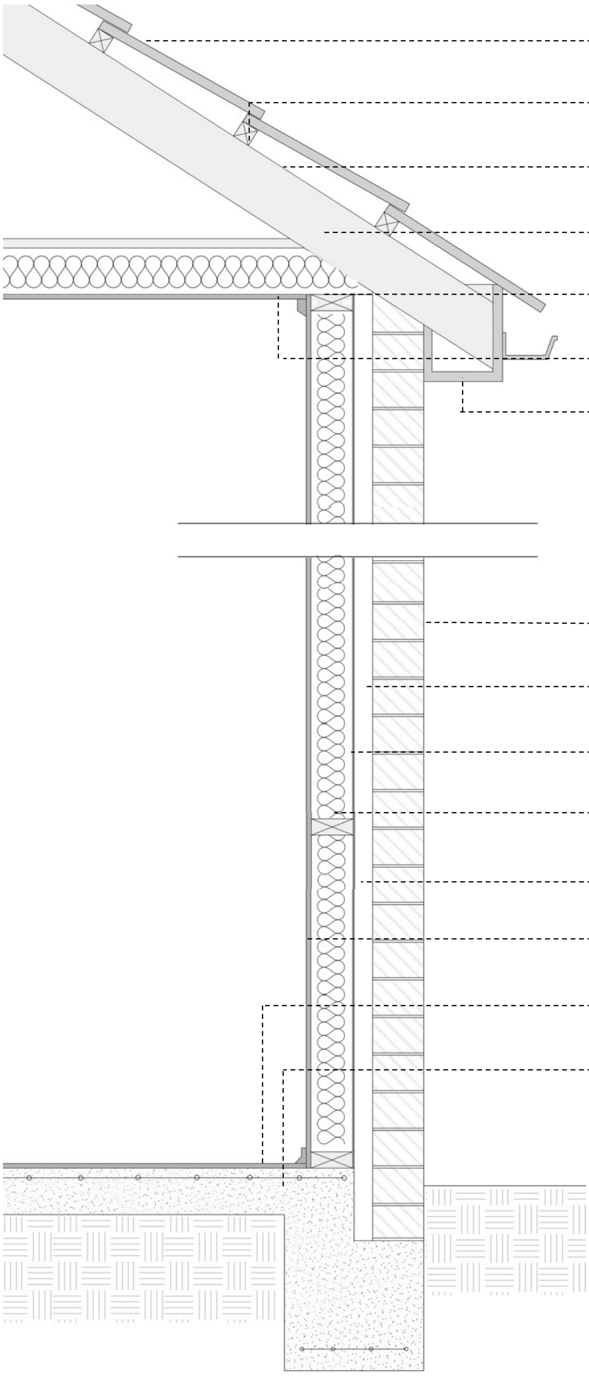


Figure 4.8 Section detail of case study building

The building is constructed with brick veneer external walls (U-value of 0.35 W/m^{2}K), concrete waffle pod ground slab and concrete roof tiles with timber trusses (U-Value of 0.23 W/m^{2}K). All windows are single glazed and aluminium framed. Insulation is provided in the external walls and ceiling with R-values of 2 and 4, respectively. Table 4.3 below provides the typical building characteristics associated with this design.

Table 4.3 Residential case study building characteristics

Building characteristic	Detail	Building characteristic	Detail
Areas and dimensions		Materials and finishes	
Area	230 m^2	External wall	Brick veneer with 90 mm timber frame
Number of bedrooms	4	Roof	Concrete tile with timber truss
Ceiling height	2400 mm	Windows	Clear single glazing with aluminium frame
Length and width	19.7 m and 14.75 m	Ground	Concrete waffle pod slab
Heating		Insulation	
Heating	Gas ducted 3 star heating unit	External wall	R2 Glasswool batts
Water heater	Solar hot water heater 200 litre	Ceiling	R4 Glasswool batts

Source: Metricon (2017)

4.2.4.2. Validation of results

Initial embodied energy and greenhouse gas emissions

The initial embodied energy (IEE) of the case study building was calculated and compared against similar previous studies. First the IEE per building element was compared against Crawford (2013), in another Path Exchange hybrid assessment (due to comparable system boundaries), as illustrated in Figure 4.9. His study, for a Melbourne-based, four-bedroom brick veneer dwelling, also found substructure, walls, fitout and roof (in descending order) to represent the largest contributors to the IEE. However, in his study the 'other items' (which refer to the multiple upstream actions such as administration etc.) did not represent the largest item, unlike the case study building results. This may be due to more materials in the substructure of his study being quantified and represented by process data (and thus less covered by pure input-output data). The ±40% variability is included in the graph to emphasise the large amount of uncertainty associated with these results. For example, the variability range for 'other items' is between 400 GJ and 1,150 GJ. The case study building IEE for 'other items' is 700 GJ, which thus falls within this expected variability range.

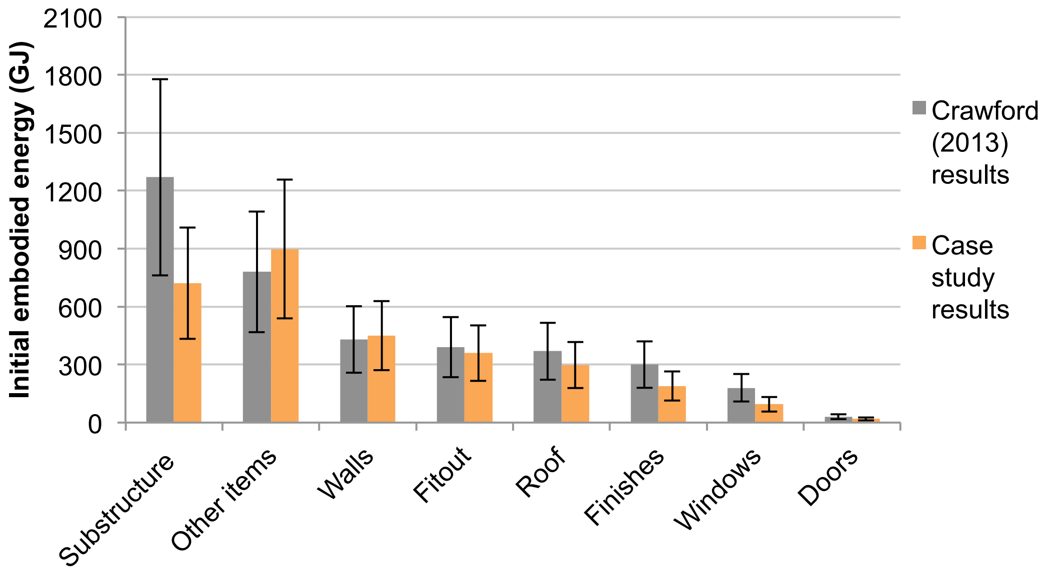


Figure 4.9 Initial embodied energy breakdown by building component with ± 40% variability: Comparison of case study results to Crawford (2013)

The IEE material breakdown between the case study results and that of Crawford (2013) was thereafter compared, as illustrated in Figure 4.10. Crawford (2013) also found that plastic, concrete and plasterboard account for a large portion of the IEE, similar to the case study building. However, his study had a much higher IEE for steel. This results from the fact that items such as door fittings, gutters, reinforcement, fascia's and internal fitout items such as shower heads were included in greater detail in his calculation (due to the availability of a detailed bill of quantities) but were not included in this study due to a lack of information for the case study building.

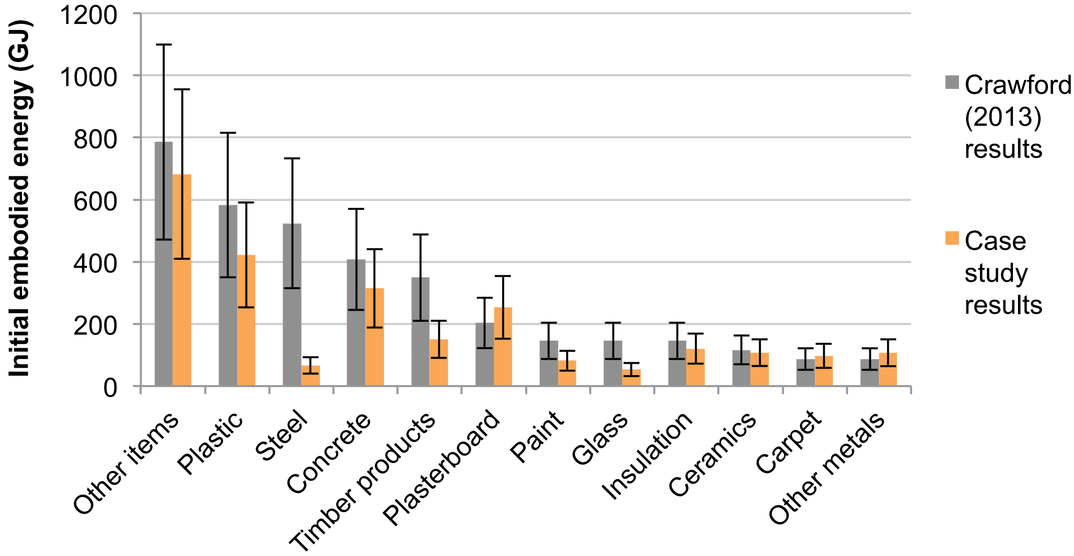


Figure 4.10 Initial embodied energy breakdown by material with ± 40% variability: Comparison of case study results to Crawford (2013)

Table 4.4 below provides an overview of similar Path Exchange hybrid IEE results for brick veneer detached dwellings. The IEE result for the case study building is very similar to the other studies with a relative difference of between 5% and 12%. As discussed previously, it is important to note that when using Path Exchange hybrid analysis there is a great level of uncertainty inherent in the calculation as emphasised in Figure 4.11 and the second last column of Table 4.4. Though ± 40% is a very large percentage of variability, Path Exchange hybrid analysis is worth pursuing due to the improved system boundary completeness when compared to other methods such as process analysis (Crawford, 2008).

Table 4.4 Comparison of initial embodied energy results

Source	IEE (GJ/m^2)	Relative difference, (%)	± 40% Variability (GJ/m^2)	Description
Case study building	12	NA	7.2 to 16.8	230m^2 4-bedroom brick veneer detached dwelling.
(Crawford, 2013)	12.98	-5%	7.8 to 18.2	307.7m^2 4-bedroom brick veneer detached dwelling.
Fay et al. (2000)	14.1	-12%	8.6 to 19.7	128m^2 two-storey brick veneer detached dwelling.
Stephan (2013)	13.16	-5%	7.9 to 18.4	297m^2 4-bedroom brick veneer detached dwelling

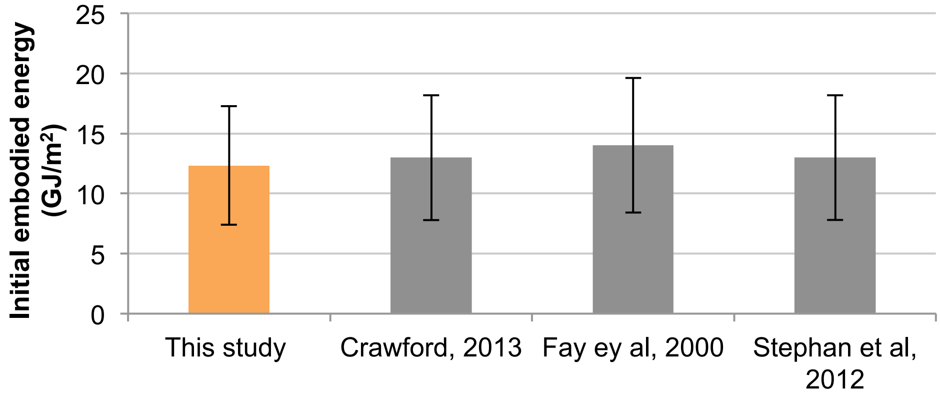


Figure 4.11 Comparison of IEE of case study results to previous studies with ± 40% variability range

With regard to the IEGHGE, Crawford (2011) estimated a total of 0.77 tCO_2e/m^2 for the brick veneer house, which is only slightly higher than the case study building, 0.73 tCO_2e/m^2. The similarity between these figures demonstrates that the framework's IEGHGE methodology has been applied correctly and the results provide comparable outcomes, bearing in mind the considerable amount of variability associated with embodied GHGE studies.

Recurrent embodied energy and greenhouse gas emissions

The recurrent embodied energy (REE) per building element was calculated for the case study building and compared to Crawford (2013), as illustrated in Figure 4.12. Similar to the case study results, Crawford (2013) also found finishes (such as paint, carpet and tiles), followed by fitout (cupboards, shower screens etc.) to account for the largest percentage of REE.

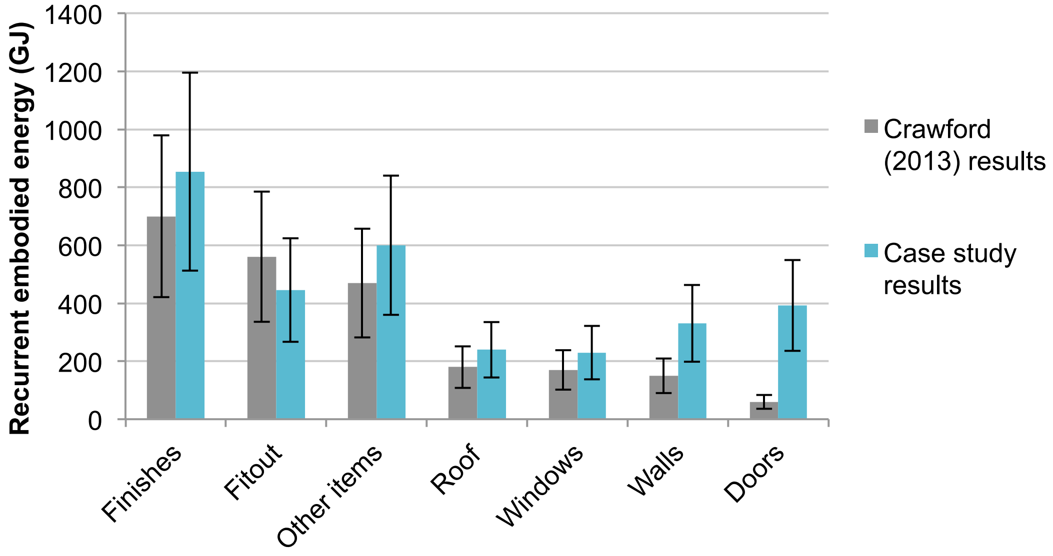


Figure 4.12 Recurrent embodied energy breakdown per building element with ± 40% variability range: Comparison of case study results to Crawford (2013)

In his comparison of the REE of the building material breakdown, Crawford (2013) also found that paint accounts for the most REE, followed by plasterboard, other items and then glass, as illustrated in Figure 4.13 below, similar to the case study building's top four REE items.

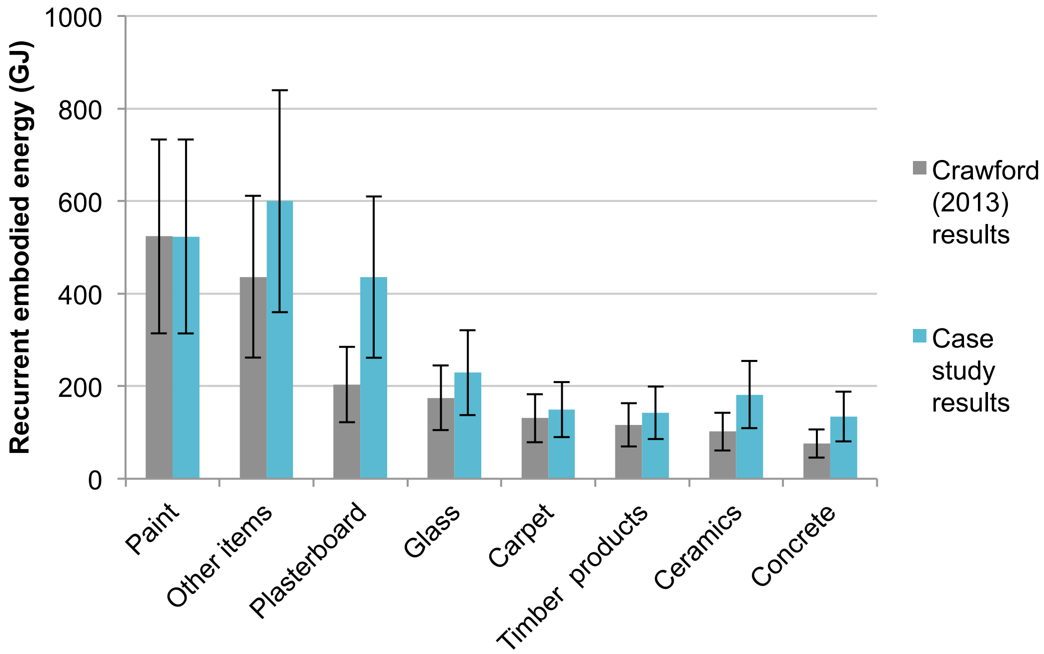


Figure 4.13 Recurrent embodied energy breakdown by material with ± 40% variability: Comparison of case study results to Crawford (2013)

Table 4.5 summarises the REE results of the earlier similar studies. The relative difference between the case study results have been included along with the ± 40% variability range. The case study REE results are higher than the other studies. This may be due to a multitude of reasons such as different replacement rates selected and price and quantity of materials. It has also been estimated that the REE can represent from 32% of the IEE (Treloar et al., 2000b) to over 70% (Stephan, 2013). The case study building's REE is approximately 79% of the IEE, which is higher than the previous studies considered. However, when interpreting REE results must consider of the considerable amount of variability surrounding embodied energy analysis. This high level of uncertainty towards REE analysis is quite apparent in Figure 4.14 below, which illustrates the variability of each study and the considerable potential overlap between the case study and these studies (as highlighted by the dotted black box). This demonstrates that the framework's REE methodology has been applied correctly and provides comparable results to other similar studies.

Table 4.5 Recurrent embodied energy comparison of case study to previous studies

Source	**REE (GJ/m^2)**	**Relative difference, (%)**	**± 40% Variability (GJ/m^2)**	**Description**
This study	9.7	na	7.2 to 16.8	Melbourne, 230m^2 4-bedroom brick veneer detached dwelling. 50 year POA.
Crawford (2013)	7.6	-30%	3.2 to 11.2	Melbourne, 307.7m^2 4-bedroom brick veneer detached dwelling. 50 year POA.
Stephan (2013)	9.6	-2%	5.7 to 13.4	Melbourne, 297m^2 4-bedroom brick veneer detached house of. 50 year POA.

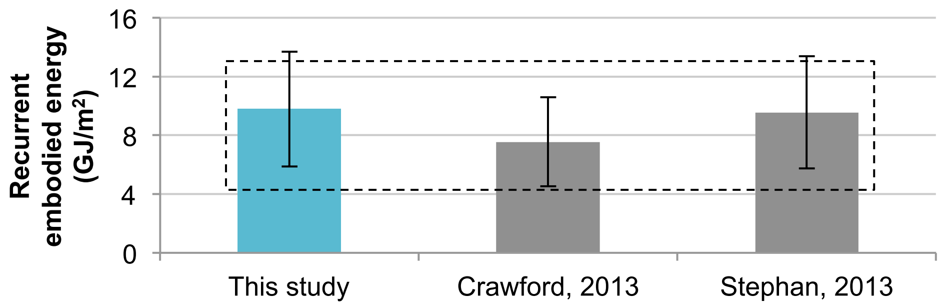


Figure 4.14 Recurrent embodied energy comparison of case study to previous studies with ±40% variability

Operational energy and greenhouse gas emissions

In order to check whether the results of the case study building's operational energy and GHGE performance are in line with other similar studies, a comparison was carried out and is summarised in Table 4.6.

Table 4.6 Primary operational energy comparison between case study and previous studies

Source	Primary energy (GJ/year)	Description	
Case study results	Unconstrained: 226	Building	230m^2 brick veneer 4 bedroom detached dwelling in Melbourne. 6 Star rating.
	Constrained: 94	Energy end use included	Lighting, appliances, heating, cooling, cooking and hot water
		Thermal simulation tool	Green Building Design Studio
DEWHA (2008)	Unconstrained: 183	Building	229m^2 brick veneer (assumed) detached dwelling in Victoria. Bedroom number unknown. Star rating unknown.
		Energy end use included	Heating and cooling only
		Thermal simulation tool	AccuRate
Beyond Zero Emissions (2013)	Unconstrained: 180	Building	165m^2 brick veneer 3 bedroom detached dwelling in Melbourne. Star rating unknown.
		Energy end use included	Lighting, appliances, heating, cooling and hot water
		Thermal simulation tool	AccuRate for heating and cooling. TRNSYS for hot water and lighting.

Source	Primary energy (GJ/year)	Description	
Ren et al. (2013)	Unconstrained: 106	Building	241 m^2 brick veneer 4 bedroom detached dwelling in Melbourne. 8 Star rating.
		Thermal simulation tool	AccuRate for heating and cooling. Manual calculations for lighting, hot water and appliances.
		Energy end use included	Lighting, appliances, heating, cooling and hot water
Crawford (2013)	Actual data: 86	Building	270m^2 brick veneer 4 bedroom detached dwelling in Victoria. 6 star rating.
		Energy end use included	Lighting, appliances, heating, cooling and hot water
		Thermal simulation tool	Not applicable. Based on gas and electricity bills

According to DEWHA (2008) the average house, assumed to be a detached dwelling of roughly 229 m^2, in the state of Victoria, Australia, consumes 76 GJ/year of delivered energy which equates to roughly 183 GJ in primary energy terms, based on an average primary energy factor of 2.4 for 50% gas and 50% electricity (Crawford, 2013). This value is assumed to be unconstrained. This study used the thermal simulation software package AccuRate (CSIRO, 2016), which only takes into account the heating and cooling operational energy needs of a building, excluding other end uses such as lighting and appliances (Delsante, 2008). It is reasonable to expect that the result will be lower than the case study unconstrained result of 226 GJ/year, which takes into account heating, cooling, lighting, appliances and domestic hot water into account. Another aspect to consider is that the thermostat set point for all zones used in the DEWHA study was 23°C, which is narrower than the case study building's thermostat settings which has an unoccupied cooling set point of 27°C and heating and cooling set points of 19°C and 24°C, respectively. A narrow thermostat set point can lead to a higher use of heating and cooling energy in order to maintain the building at the desired internal temperature (Tyler et al., 2014). Gaceo et al. (2009) found that for every 1°C difference, energy consumption can vary by as much as 7%. Beyond Zero Emissions (2013) resulted in an operational performance similar to that of DEWHA, however the building is much smaller (165 m^2).

In another Melbourne-based study was completed by Ren et al. (2013), their unconstrained result is lower than the DEWHA and Beyond Zero Emissions studies discussed above, and the case study building. This can be expected as this house is rated at 8 Stars (according to the national NatHERS scheme), and deemed more energy efficient than the case study (which is rated at 6 Stars). This dwelling also uses double glazed windows (the case study and other studies make use of less energy efficient single glazed windows), which can contribute to lower operational energy results. It is important to be aware of other factors such as the thermostat set point, which was between 22°C and 26.7°C. This is a wider set point than that used in many of the other studies, which, as discussed before, can result in lower energy requirements.

All the studies discussed above, including the case study building, are based on thermal simulation software and represent the expected energy use, not the actual data. Beyond Zero Emissions (2013) states that simulated energy demands are often over-estimated by a ratio of about 2:1. The simulated results therefore represent a higher energy demand than typical households. If this ratio is applied to the case study building results, the result will be reduced to 113 GJ/year. Other studies confirm this overestimation but in varying degrees. Ilie et al. (2016) states that thermal simulation can overestimate by between 15% and 25%. Maamari et al. (2006) and Reeves et al. (2012) state that an acceptable percentage difference between simulated and measured results is 15%. Knight et al. (2007) found an overestimation of 50%. In contrast Newsham et al. (2009) found that simulated buildings underestimate energy consumption by between 18% and 39%, when compared to actual buildings. Norford et al. (1994) found that building simulation underestimates actual energy use by as much as 150% (mainly due to the unanticipated occupant energy use due to extended hours of occupation and increased number of electronic equipment items). However, this study is from a commercial building perspective and dates back to 1994. It can be expected that the reliability of simulation tools has matured since then. Another method of addressing the variability of simulation results is the application of a 'constraint factor', as discussed in Chapter 3. The constraint factor is multiplied by the primary energy figure in order to provide a more realistic operational energy consumption value considering occupancy factors. When the constraint factor is applied to the case study building, the primary energy demand is reduced to 94 GJ/year.

Crawford (2013) provides an example of actual energy results based on a household's bills. His study included heating, cooling, lighting, domestic hot water and appliances, similar to the case study building. However his results are much lower than the other studies, at 86 GJ/year. This may be due to the fact that it can be seen as a constrained value, as it is based on actual bills and not predicted energy usage (in comparison to the other studies unconstrained results). His study's results are only slightly lower than the case study constrained value of 94 GJ/year. Other factors that could also have lead to a decreased energy usage is the fact that the house used in his study has highly insulated walls with a very efficient instantaneous gas-boosted solar hot water system, a five-star gas ducted heating system and an evaporative cooling system, as illustrated in Figure 4.15 below.

When interpreting operational energy results it is important to consider the considerable amount of variability associated with them. Factors such as occupancy schedules, temperature set point, number of conditioned rooms, lighting and power density, efficiency of HVAC system vary greatly in actual building use and are a likely source of variability for all simulations (Reeves et al., 2015). Purdy and Beausoleil-Morrison (2001) found that the major factors affecting residential energy simulation are zoning (for example whether one zone or multi-zone is used), thermal bridging, infiltration, external temperature and ground reflected solar radiation. Different simulation software can also yield different results based on internal calculations and databases. Another critical problem is that simulation tools either tend to either overestimate or underestimate energy consumption, as discussed above. By applying the constraint factor to the simulated result, some of this overestimation can be decreased and reflect a more realistic value. However, due to the variability and uncertainty of energy consumption predictions Pettersen (1994), Juodis et al. (2009) and Crawford (2013) have suggested a variability range of ±20% when simulating operational energy results. Figure 4.15 illustrates the case study's constrained primary operational energy demand and Crawford (2013) actual primary operational energy demand (both studies using very similar buildings within Victoria) along with the ±20% variability range.

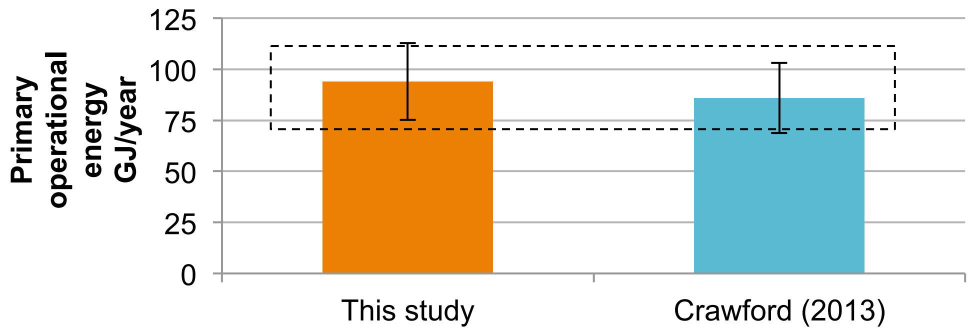


Figure 4.15 Comparison of case study constrained result to Crawford (2013) with ±20% variability range

Due to the significant amount of overlap (illustrated by way of the dotted black box) between the case study results and Crawford (2013), it can be concluded that the framework's operational energy methodology has been applied correctly and provides comparable outcomes.

4.3. Summary

This chapter provided an overview of the tasks that had to be performed to integrate the environmental and economic building evaluation into a single framework. First, the key requirements of the framework were defined (as based on the gaps from the earlier studies). Thereafter, the framework approach was defined, drawing upon the frameworks discussed in Chapter 3, such as LCA, LCC and MCDM, and the frameworks were combined to create the 9 steps this study's framework approach. The framework's approach starts with defining the goal and scope of assessment (which is similar to the first step of LCA and MCDM) and concludes with the performance of a sensitivity analysis (similar to the final steps of LCA and LCC) and the selection of an appropriate option (similar to MCDM final step). The input parameters of the framework (based on the quantification methods selected in Chapter 3) were defined and categorised as either pre-defined or user defined inputs. The final section of this chapter included the validation of the LCA quantification techniques that were selected as part of the framework. This was achieved by applying the LCA quantification methods to a case study building (a residential detached building) and comparing the case study results against other similar studies. It was concluded that the quantification methods have been applied correctly and that they provide reliable and comparable results. Further detail pertaining to the LCC validation of results is provided in the next chapter where the framework is applied to the case study building used in this chapter, in order to demonstrate how the framework can be used and to demonstrate its potential.

5.

Demonstration of the framework

5.1. Introduction

The previous chapter discussed the various factors involved in developing a framework for the integration of the environmental and economic performance of buildings, including the calculation methods, input parameters, and possible visual outputs. The aim of this chapter is to apply the integrated LCA and LCC framework to a building case study in order to:

- Provide an example of the results that can be obtained by using an environmental and economic integrated framework.
- Provide an example of how such a framework can advise the decision-making process and guide the final selection of a building design option.
- Demonstrate how this final selection can be advised by the user’s personal preferences.
- Provide an example of how this framework can be used to demonstrate the trade-offs and relationship between environmental and economic factors.
- Demonstrate the capability of the framework and its ability to analyse different design options in different locations and indicate which option is most suited to the assessed building/project.

The aspects included in this demonstration are illustrated in Figure 5.1. This included applying the framework to a case study building, in this instance a residential building. The majority of Australia’s direct GHGE from buildings were from residential buildings in 2016 (Department of the Environment and Energy, 2016). This type of case study also addresses two gaps from previous studies (referred to in Chapter 3 and 4): most previous frameworks or environmental and economic assessments are applied to exemplar buildings, not traditional buildings (which make up most of the building stock), and the assessment is based on (and applicable to) the building scale, not just product or material scale as in previous studies.

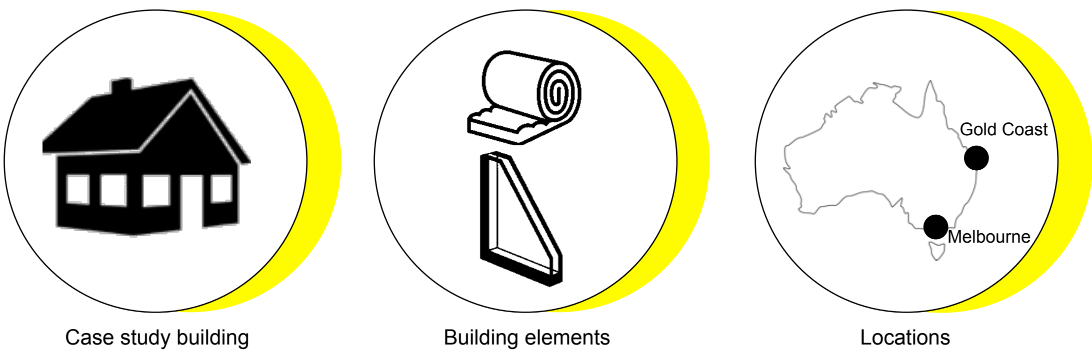


Figure 5.1 Aspects included in the demonstration of the integrated framework

The next aspect of this demonstration was the application of the framework to different building elements, namely insulation and glazing (both are popular strategies in the reduction of operational GHGE (OGHGE) but rarely assessed from a life cycle perspective). Demonstrating the framework's capability in assessing different design decisions. The final aspect was locating the building case study and its associated building elements in two different locations, being Melbourne (a temperate climate) and Gold Coast (a subtropical climate). Geographic location can influence the heating and cooling needs of a building and other data inputs, such as fuel mix and price of goods (Dixit et al., 2011). By applying the framework to two different locations, its flexibility and potential was further showcased together with highlighting the importance of contextual considerations to life cycle design.

The structure of this chapter includes a description of the case study followed by the results of the application of the framework to this case study. The insulation results (for both Melbourne and Gold Coast) are followed by the glazing results. These results are used as the basis for the discussion in Chapter 6.

5.2. Selection of case study

The function of a building, the type of materials used and a building's location are often quoted as being the key determinants of a building's LCGHGE (Chastas et al., 2016; Ramesh et al., 2010; Islam et al., 2015a). During the course of the design and construction phases numerous decisions have to be made by the user. These key design decisions (i.e. building, materials and location) form the basis of the case study selection. Refer to Section 4.2.4 for justification of the case study research approach.

5.2.1. Residential building case study

A residential building, specifically detached dwellings, was selected as almost 80% of all people in Australia live in detached dwellings (Australian Bureau of Statistics, 2012). From a regional perspective, in areas like the Melbourne Metropolitan Area, single detached dwellings constitute 92% of the residential building stock (GA, 2012). In Australia, the increasing population (of roughly 400,000 people a year) will contribute to a demand for an estimated 5.4 million additional dwellings over the next 30 years, which equates to 180,000 dwellings per annum (Property Council of Australia, 2015; Krockenberger, 2015). There is an urgent need to ensure that the residential buildings being built aim to reduce GHGE as much as possible.

Approximately 90% of these dwellings have 3 or 4 bedrooms (Robb and Lucas, 2016) with brick veneer construction representing 70% of the residential stock (Beyond Zero Emissions, 2013). The selection process for the case study building had to satisfy the requirements of representing a typical Australian residential dwelling, to ensure that the Base Case results are generalised and applicable to as many of buildings as possible. For this reason the same residential building used in the validation section was used for this Chapter's demonstration (refer to Chapter 4 Section 4.2.4.1 for case study building description, Figure 4.6 for render of building, Figure 4.7 for a plan of the building and Figure 4.8 for a section of the building). Refer to Table C1 in Appendix C for the bill of quantities of the residential case study building.

5.2.2. Building elements

The term 'building elements', as used in this chapter, refer to building material elements (such as brick or concrete), building mechanical elements (such as mechanical cooling devices), building elements relating specifically to the energy efficiency (such as passive design solutions (PDS) such as insulation) or renewable energy systems (such as photovoltaics). Several studies have discussed the importance of adopting the energy hierarchy and implementing PDS first within any building design that aims to reduce energy demand and associated GHGE (followed by active and renewable measures), particularly at an early stage, to ensure the creation of lower carbon built structures (refer to energy hierarchy in Figure 2.3) (Davis Langdon, 2013; Attia et al., 2012). However, the selection of PDS has largely focussed on decreasing a building's OGHGE (often disregarding the embodied GHGE), and cost decisions have been primarily based on the initial cost (often disregarding the whole life cycle cost) (Langston and Langston, 2008; Jackson, 2008). A crucial issue for both owners and occupiers is the 'cost-effectiveness' of low carbon solutions (Ellis, 2009). Financial justification is required to increase the uptake of life cycle environmental optimisation strategies (Warren-Myers, 2012). Several popular Australian home-builders, like Metricon, offer PDS as optional extras at an additional cost (Metricon, 2017). Some of these options include improved insulation levels (either with an increased thermal resistance, R-Value, or different materials) or replacing the standard design inclusion of single glazing with double glazing (Metricon, 2017; Porter Davis, 2011; Simonds, 2016; PEET, 2015). Insulation is regarded as one of the most cost effective measures to reduce carbon emissions associated with buildings (Williams, 2012). A recent survey indicated that almost 70% of Australian homes have insulation (Australian Bureau of Statistics, 2014b) and all new homes being built have to meet the insulation guidelines set by the Australian Building Codes Board (2015b). Homeowners are faced with multiple decisions and questions regarding insulation, such the R-Value that is to be selected, which material and the cost of improving the R-Value. The integrated framework can be used to help answer these questions. Another popular PDS is glazing. Several studies have discussed the energy and GHGE inefficiency of single glazing in particular climates and the improved performance of other glazing options for example double glazing, triple glazing or glass treatments such as tinting (Citherlet et al., 2000; Beyond Zero Emissions, 2013; Edge Environment, 2013). There is still great uncertainty among homeowners regarding the cost-effectiveness and potential to reduce GHGE, with only 2.6% of Australian dwellings having double-glazing in 2008 (the most recent available statistic) (Australian Bureau of Statistics, 2008). For this reason, insulation and glazing have been selected for further analysis in this chapter, as part of the residential building case study. This is in order to demonstrate how the framework can be applied to different building related decisions, providing an indication of the possible results that can be achieved by its use and demonstrating how these building elements can be selected based on an integrated life cycle approach for optimising the GHGE and cost of a building.

5.2.2.1. Building element: Insulation

The two main categories of insulation are bulk insulation and reflective insulation. Reflective insulation consists of a layer of foil (usually made from aluminium) and helps to reduce heat transferred by radiation. Bulk insulation helps to reduce the heat transfer through conduction. Common types of bulk insulation materials used in Australia, according to McGee and Mosher (2013) include: glasswool (made from melted glass), rockwool (made from melted volcanic rock), polyester (made form polyester threads), wool (made from sheep's wool), cellulose fibre loose-fill (made from pulverised recycled paper) and expanded polystyrene (EPS) (made from polystyrene beads).

The thermal resistance (R-Value) of insulation plays a critical role in determining the effectiveness of its ability to help reduce heat loss and therefore help reduce the operational energy and GHGE associated with buildings (Özkan and Onan, 2011; Tettey et al., 2014). R-Value (m^2K/W) is determined by dividing the thickness of the material by the thermal conductivity (W/m.K). Generally, the higher the R-Value the better the thermal performance of the material or assembly. In Victoria, the minimum total R-value required for an external wall for residential buildings is R 2.8 $m^2.K/W$

and for a ceiling R 4.1 m^2.K/W (Australian Building Codes Board, 2015a). The residential building case study is provided with R2 m^2.K/W glasswool insulation (resulting in an overall total R-Value of the external wall of R2.9 m^2.K/W) and R4 for the ceiling (Metricon, 2017), which forms the Base Case insulation scenario (i.e. the business as usual scenario based on the type of insulation provided as part of the case study building). However, higher R-Values are provided as options to improve the thermal performance of the building. Other voluntary energy efficient standards such as Passivhouse (Straube, 2009) typically use much higher R-Values, such as between R4 and R6 for walls and R5 and R10 for ceilings. Therefore, insulation manufacturers often provide a range of R-Value options. The corresponding thickness of the insulation tends to increase as the R-Value increases (based on the same density). An increase in R-Value will lead to an increase in material quantity, which has been demonstrated to increase the embodied energy of a building (as embodied energy is directly related to the quantity of the material) (Sturgis and Roberts, 2010). It is crucial to understand the LCGHGE implications of various R-Value applications. Different R-Values and materials will affect the initial and recurrent embodied and operational energy and GHGE. Different R-values will also affect the LCC of the building, as the quantity of material (due to the thickness and density of the different R-Values) will increase the total cost of the material.

Table 5.1 provides a summary of the insulation scenarios tested in this Chapter's demonstration. In order to test the influence of different insulation materials on a building's LCGHGE and LCC, the Base Case R2 and R4 glasswool insulation was compared to EPS and straw insulation. Straw was selected due to its low environmental impact. It is generally a waste product and the GHGE associated with its production are very low (Downton, 2013). In contrast to straw, expanded polystyrene (EPS) has a much better thermal conductivity value (less material will have to be used) but it has a very high embodied energy content (it is about 5 times more energy intensive than straw and 3 times more than glasswool to manufacture, based on input-output hybrid data (Treloar and Crawford, 2004)). Refer to Table C2 in Appendix C for more detail regarding the embodied energy coefficient, wastage factor, 2017 AUD costs and material service life of the insulation scenarios. In order to test the influence of different insulation materials on the buildings LCGHGE and LCC, the Base Case R2 and R4 glasswool insulation was compared to EPS and straw insulation.

Table 5.1 Insulation scenarios tested for framework demonstration

Insulation scenario	**Detail**	
	R Value (m^2K/W)	Material
Base Case[1]	Wall: R2 Ceiling: R4	Glasswool
EPS	Wall: R2 Ceiling: R4	Expanded polystyrene
Straw	Wall: R2 Ceiling: R4	Straw
R3 Wall	Wall: R3 (Ceiling: R4)	Glasswool
R5 Ceiling	(Wall: R2) Ceiling: R5	Glasswool
R6 Ceiling	(Wall: R2) Ceiling: R6	Glasswool

Source: [1] *Metricon (2017)* [2] *Crawford (2011)* [3] *Beyond Zero Emissions (2013)* [4] *Australian Building Codes Board (2015a)*

5.2.2.2. Building element: Glazing

Glazing forms an integral part of most building designs as it provides the user with a connection to the outdoors and provides light and ventilation. However up to 40% of a home's heating energy can be lost and up to 87% of its heat gained through glazing (McGee, 2013). A vital part of the efficiency of glazing is its U-Value (which indicates the rate of heat loss), which is measured W/m^2K. The efficiency of glazing can be improved by lowering the U-Value as this results in a greater resistance to heat flow. Double or triple glazing have lower U-Values than single glazing, but they also have a higher embodied energy and GHGE as more materials are required. The embodied energy and GHGE is often ignored in glazing energy/ GHGE assessments (Hee et al., 2015; Gorantla et al., 2017). The difference in financial cost between single and double-glazing varies from 50% to 100%, depending on style and manufacturer (Green, 2011). The type of frame selected has also been demonstrated to affect both the embodied and operational energy and associated GHGE (Asif et al., 2011; Citherlet et al., 2000). As stated previously, most residential dwellings in Australia are equipped with single glazed windows and aluminium frames. Increasing awareness of building energy efficiency has resulted in more and more homeowners making the decision to select improved glazing options. A survey completed in 2012 reported that almost 40% of households interviewed wanted to install window treatments (such as double glazing refurbishment or tinted windows) (ABS, 2013). Volume builders are starting to include optional extras such as double-glazing or tinted glass albeit at an increased cost (Metricon, 2017; Metricon, 2005; Porter Davis, 2011). This increased initial cost, which tends to dominate a homeowner's selection process, often affect the uptake of these more energy efficient building options (Menzies and Wherrett, 2005).

The Base Case for the residential case study uses single glazed windows with aluminium frames (SG_AF). Various types of glazing scenarios (ranging from single to triple) and different types of frames (aluminium and timber) have been tested in this chapter, based on the alternatives most commonly available in Australia (McGee, 2013), as summarised in Table 5.2. Glazing extent remained constant throughout all scenarios. Refer to Table C4 in Appendix C for more detail regarding the embodied energy coefficients, MSL and wastage factors used for the glazing scenarios.

Table 5.2 Glazing scenarios tested for framework demonstration

Glazing scenario	**Detail**	
	Type	U-Value[2] ($W/m^2.K$)
SG_AF (Base Case)[1]	Single glazing, aluminium frame	6.9
SG_TF	Single glazing, timber frame	5.5
DG_AF	Double glazing, aluminium frame	4.2
DG_TF	Double glazing, timber frame	3.0
TG_AF	Triple glazing, aluminium frame	1.53
TG_TF	Triple glazing, timber frame	0.6

Sources: [1] *Metricon (2017),* [2] *McGee (2013)*

5.2.3. Locations

As discussed earlier in Section 5.2, the geographic location has a significant influence on the operational energy and GHGE of a building, due to the climate specific heating and cooling demands. Other context specific factors, such as the fuel mix and price of goods also have an influence on the LCGHGE and LCC of a building. Two different Australian locations have been selected to demonstrate the framework, to show that the framework is applicable to more than one location and to highlight how context specific factors can influence the framework results. The locations selected for this study are Melbourne, with a temperature oceanic climate and Gold Coast, with a humid subtropical climate, as illustrated in Figure 5.2. Table 5.3 provides further geographic detail about the mean and minimum temperatures and energy mix etc. Other than climatic differentiation, it is also estimated that property price is 5% lower in Gold Coast than in Melbourne (Rawlinsons, 2017), and that consumer prices are between 7% (Numbeo, 2017) and 14% (Expatistan, 2017) lower in Gold Coast when compared to Melbourne, which can have an impact on both the LCC results and the LCGHGE results (as the hybrid embodied energy and GHGE quantification techniques use the price of goods as per Equation 3.5).

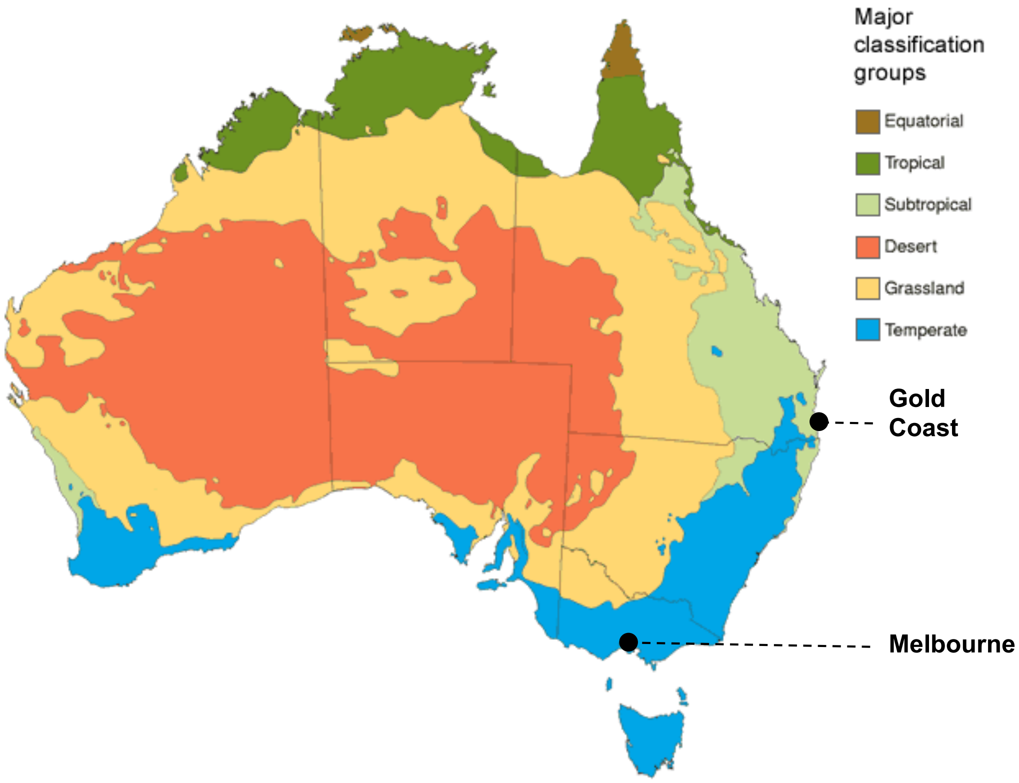


Figure 5.2 Selected geographic locations for framework demonstration

Table 5.3 Melbourne and Gold Coast geographic details

Detail	Melbourne	Gold Coast
Mean max temperature	20.4°C[1]	25.1°C[1]
Mean min temperature	11.4°C[1]	17.2°C[1]
Energy mix and primary energy emission factor (EF) for CO_2	Brown coal[2] EF: 92.7 Natural gas[2] EF: 51.2	Black coal[3] EF: 90 Natural gas[3] EF: 51.2
BCA Climate Zone	6[4]	2[4]
Coordinates	37.8136°S, 144.9631°E	28.0167°S, 153.4000°E

Sources: [1] Bureau of Meteorology (2013), [2] Environment land water and planning (2017), [3] Department of industry (2016), [4] Australian Building Codes Board (2015a)

5.3. Case study results

The previous section provided a brief description of the case study building and building elements (insulation and glazing) and locations (Melbourne and Gold Coast). The following section provides the LCGHGE and LCC results as quantified according to the integrated framework developed in Chapter 4.

The aim of this section is to demonstrate how the framework can be applied to a specific built environment project, to provide an example of the results that can be achieved by such a framework and to indicate how this framework can demonstrate the trade-offs between environmental and economic performance. This section also shows how this framework can guide the decision-making process from an integrated life cycle perspective.

The insulation results, applied to the residential case study building (for both the Melbourne and Gold Coast locations) have been discussed first, followed by the glazing results. The various steps involved with the framework process have been described for both the insulation and glazing scenario results and this chapter concludes with a sensitivity analysis.

5.3.1. Insulation scenario results

The framework approach, discussed in Chapter 4, has been applied to the residential case study building, as illustrated in Figure 5.3. Figure 5.3 provides an example of how the integrated framework approach can be moulded to the specific enquiry at hand (which, in this case, is to identify the insulation option which is most likely to decrease LCGHGE). Each step has been explained in more detail below.

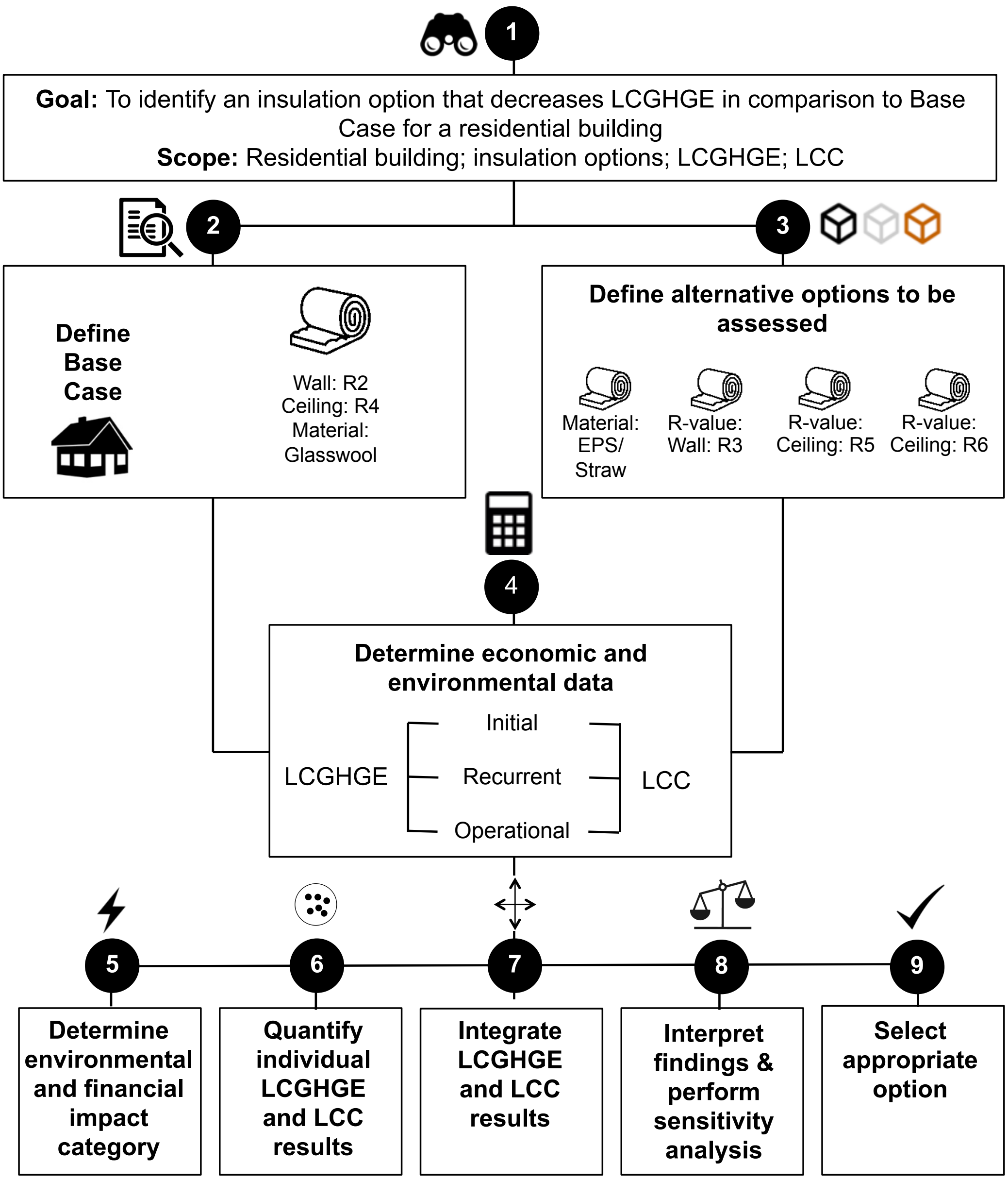
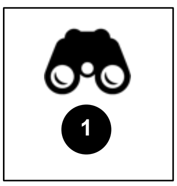


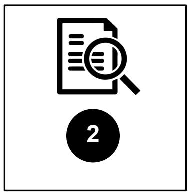
Figure 5.3 Framework approach for residential insulation scenario analysis

5.3.1.1. Step 1: Define the goal and scope of the assessment



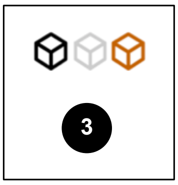
The first step, as per Figure 5.3, is to define the goal and scope of the assessment. The goal of the assessment is to determine which insulation option results in a decrease of the building's LCGHGE when compared to the Base Case and to assess the LCC implication of these insulation options. The scope of the assessment for the LCGHGE analysis includes the building's total embodied GHGE (including initial and recurrent) and operational GHGE (which includes heating, cooling, lighting, appliances, hot water and ventilation). The scope for the LCC included the initial cost, operational cost and replacement costs.

5.3.1.2. Step 2: Define the Base Case



For Step 2, Base Case needs to be defined. This refers to the Base Case building characteristics for the residential case study building. Refer to Chapter 4 for a description of the main building characteristics and to Table C1 in Appendix C for the bill of quantities for the case study building. The case study building also includes defining the Base Case insulation (type of material and R-Value). According to the case study building developer, Metricon, R2 glasswool insulation was used in the external walls and R4 for the ceiling, being a standard inclusion that meets the current building regulation of Australia (Australian Building Codes Board, 2015a). Refer to the validation section in Chapter 4 (see Section 4.2.5.2) for a breakdown of the Base Case LCGHGE values.

5.3.1.3. Step 3: Define alternative options to be assessed



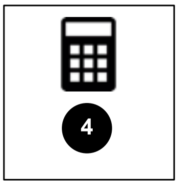
The next step is to define the alternative insulation options that are to be tested for the residential building. As stated before in Section 5.2.2, the R-Value and type of material have an impact on the building's LCGHGE and LCC. For these reasons different options for each of these aspects have been investigated. The different R-value options (all based on glasswool) that a user would potentially consider were based on one of the largest insulation suppliers in Australia, namely Fletcher Insulation (2016). For the walls the R-Value was upgraded from R2 to R3 (based on what was available from the supplier). For the ceiling the R-Value ranges from R4 to R6. Different materials have also been tested, namely EPS and Straw. All insulation scenarios have been summarised in Table 5.1. Figure 5.4 provides an example of what section of the case study's bill of quantities (as provided in Table C1 in Appendix C) is adjusted for the insulation scenario analysis (i.e. the rows corresponding to the insulation are modified according to each insulation type tested). The timber frame (which is 90mm wide for the Base Case) is also adjusted for insulation options requiring a wider frame (due to thicker insulation being required for higher R-Values such as R3, R4 or R5).

Component	Material	Material Quantity	Material Quantity unit	Embodied energy coefficient (GJ/unit)[1]	Wastage multiplier[1]
Foundation, ground floor					
Ground floor	Concrete slab	48.00	m^3	4.44	1.1
	Polystyrene waffle pods	40.54	m^3	7.04	1.05
	Steel reinforcement Bar	0.34	t	85.46	1.05
	Steel reinforcement Mesh	0.37	t	85.46	1.05
	Plastic membrane	229.00	m^2	0.51	1.05
External wall					
External cladding	Clay brick	165	m^2	0.56	1.05
Wall ties	Stainless Steel	0.04280	t	85.46	1.05
Insulation	Aluminium Reflective foil	134	m^2	0.14	1.1
	R2 Fibreglass insulation	11	m^3	2	1.1
Internal lining	Plasterboard	150	m^2	0.21	1.05
Timber f					
Framing					
Internal					
Finish					
Roof					
Tiles					
Insulation					
Frame: Rafters & ridge beams					
Purlins/ Girders	Softwood	0.38	m^3	10.9	1.02
Insulation	Glasswool ceiling batts, R4	44.00	m^3	2	1.1
Finish	Plasterboard	226	m^2	0.21	1.05
Gutter	Steel	0.021	t	0.933	1.05
Windows					
Frame	Aluminium	0.15	t	252.6	1.1
Glass	Clear	30	m^2	1.73	1.03

External wall					
External cladding	Clay brick	165	m^2	0.56	1.05
Wall ties	Stainless Steel	0.04280	t	85.46	1.05
Insulation	Aluminium Reflective foil	134	m^2	0.14	1.1
	R2 Fibreglass insulation	11	m^3	2	1.1
Internal lining	Plasterboard	150	m^2	0.21	1.05

Figure 5.4 Section of the bill of quantities modified for insulation scenarios

5.3.1.4. Step 4: Determine economic and environmental data



Step 4 requires the economic and environmental data for the assessment to be determined. This section relates calculations and identified framework input parameters set out in Chapter 4 (Section 4.2.4). The environmental data, is the data required to quantify the LCGHGE, is discussed first, followed by the economic data (which refers to the data required to quantify the LCC). Only the user defined inputs (i.e. the data inputs that depend on the type of user and the type of project) are discussed below. Refer to Table B1 to B11 in Appendix B for an example of the predefined inputs (i.e. data that will remain consistent regardless of user and type of project).

Environmental data for residential insulation assessment

The information in Table 5.4 provides an overview of the user defined input parameters and associated data used to quantify the LCGHGE for the case study building. Table 5.4 describes the type of data required to complete the LCGHGE analysis that forms part of the integrated assessment.

Table 5.4 User defined input parameters for insulation scenarios assessment: environmental data

Life cycle category	User defined input parameter	Residential building case study data
Initial embodied GHGE Refer to Equation 3.1 to 3.4	Area of building	230m^2 (Metricon, 2017)
	Quantity of material (Q_m)	This has been extracted from Revit (Autodesk, 2016) and based on the residential case study building (refer to Chapter 4 and Table C1 in Appendix C). Revit is used due to the time efficiency and reliability this BIM software provided in aiding BOQ generation (Nadeem et al., 2015; Abanda et al., 2015).
	Total energy requirement of building sector $(TERBS)$	10.633 GJ/AUD1000 (Crawford, 2011)
	Total energy requirement of material $(\sum_{m=1}^{M} TER_m)$	5.6530 GJ/AUD1000 (as detailed in Table C6 in Appendix C) based on the latest available energy based input-output model for Australia (Crawford and Treloar, 2010).
	The remainder $(\mathrm{TERBS} - \sum_{m=1}^{M} \mathrm{TER}_m)$	Based on the total energy requirement of the residential building sector (TERBS) being 10.633 GJ/A$1000 (pre-defined input) and the TER_m being 5.653 GJ/AUD1000, the remainder equals 4.98 GJ/AUD1000.
	Cost of building (C_b)	Based on Rawlinsons (2017) and is for a 4 bedroom Melbourne based standard finish brick veneer house of AUD1155/m^2. The equivalent 1997 price (that is required in order for the price to correlate with the latest available energy based input-output 1996-1997 model for Australia) is AUD586/m^2, once the building cost index (embedded input) was applied. It is assumed there is a decrease of 5% in property price for Gold Coast (Rawlinsons,

Life cycle category	User defined input parameter	Residential building case study data
		2017).
Recurrent embodied GHGE Refer to Equation 3.5	Period of analysis (POA)	A POA of 50 years has been selected which is in line with other similar studies such as Crawford et al. (2016), Rauf (2015), Gustavsson et al. (2010) and Fay et al. (2000). It is assumed that at the end of 50 years the dwelling would be at the end of its useful life and ready for demolition. The sensitivity of this is tested with a POA of 20 and 100 years, respectively.
	Cost of material (C_m)	The prices are based on Rawlinsons (2017).
Operational GHGE Refer to Equation 3.8	Annual energy use	Dynamic simulation with the use of Green Building Studio (GBS) was used to estimate the operational energy and subsequent GHGE. GBS was selected due to its suitability to early stage design and seamless integration with Revit (Adams, 2013) (refer to Chapter 2 Section 2.3.2 for more detail) and the fact that dynamic simulation (instead of steady state calculations) is better at taking factors such as thermal mass and solar radiation into account providing more realistic results (Van der Veken et al., 2004). Refer to Table C9 in Appendix C for assumptions.

Economic data for residential insulation assessment

The information in Table 5.5 provides an overview of the user defined input parameters and associated data used to quantify the LCC for the case study building. The data in Table 5.5 provides an example of the type of data required to further complete the LCC analysis that forms part of the assessment. Refer to Equation 3.12 for more detail on the use of this data.

Table 5.5 User defined input parameters for insulation scenarios analysis: economic data

Life cycle category	User defined input parameter	Residential building case study data
Initial cost	Area of building	Refer to Table 5.4
	Quantity of material	Refer to Table 5.4

<table>
<tr><th>Life cycle category</th><th>User defined input parameter</th><th>Residential building case study data</th></tr>
<tr><td></td><td>(Q_m)</td><td></td></tr>
<tr><td></td><td>Price of building
(P_b)</td><td>Refer to Table 5.4</td></tr>
<tr><td>Recurrent cost</td><td>Period of analysis
(POA)</td><td>Refer to Table 5.4</td></tr>
<tr><td></td><td>Cost of material
(C_m)</td><td>Refer to Table 5.4</td></tr>
<tr><td></td><td>Inflation rate
(i)</td><td>The inflation rate for Australia has averaged 5.15% from 1951 to 2015 (with the lowest rate recorded at -1.30% in 1962 and the highest of 23.90% in 1951) (Trading economics, 2016). The inflation rate recorded for January 2016 was 1.7% with an expected increase to 2.3% by the end of 2016. Three recent Australian LCC studies used the average of Australia’s inflation rate over the last 10 years, roughly 3% (Islam et al., 2015a; Ren et al., 2016; Morrissey and Horne, 2011). For this study 3% has been used. The sensitivity of this value has been tested in the sensitivity analysis.</td></tr>
<tr><td></td><td>Discount rate
(r)</td><td>Mithraratne et al. (2007) has stated that the average discount rate value for Australia is between 5 and 9%. Recent Australian based studies have used a value between 6% to 8% (Baniyounes et al., 2012; Morrissey and Horne, 2011; Islam et al., 2015a). Based on the equations presented in Chapter 3 this study uses a discount rate of 6%. The sensitivity of this value has been tested in the sensitivity analysis.</td></tr>
<tr><td>Operational cost</td><td>Energy type
(ED_v)</td><td>Electricity and gas (Metricon, 2017)</td></tr>
<tr><td></td><td>Cost of energy
(C_v)</td><td>Based on 2017 Victorian energy prices from Energy Australia (2017).
<table>
<tr><th>Energy type</th><th>Detail</th><th>Price (2017)</th></tr>
<tr><td>Gas</td><td>Winter rate</td><td>2.43 cents/MJ</td></tr>
<tr><td></td><td>Non-winter rate</td><td>1.72 cents/MJ</td></tr>
<tr><td>Electricity</td><td>Peak (7am-11pm)</td><td>31.28 cents/kWh</td></tr>
<tr><td></td><td>Off-peak</td><td>15.16 cents/kWh</td></tr>
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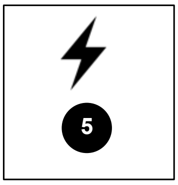
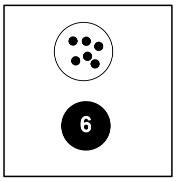
5.3.1.5. Step 5: Determine environmental and economic impact category



Step 5 requires the selection of an environmental and economic impact category. For this study, global warming potential (GWP) (tCO_2e) has been selected for the LCGHGE indicator and AUD 2017 for the LCC indicator.

5.3.1.6. Step 6: Quantify life cycle greenhouse gas emissions and life cycle cost results



The next step was to quantify the LCGHGE and LCC of the Base Case and for each alternative insulation scenario. The LCGHGE results are discussed first, followed by the LCC results. The aim of this section is to demonstrate the results that can be achieved by the quantification techniques (like the hybrid approach for the embodied GHGE calculations and the NPV approach for LCC), selected in Chapter 3, to be used within the framework.

Life cycle greenhouse gas emissions results

The quantification techniques described in Chapter 3 (refer to Equations 3.1 to 3.11) were used to provide the results for this Section. Refer to Table 5.1 for a detailed description of the insulation scenarios tested. Figure 5.5 illustrates the LCGHGE breakdown of the insulation scenarios in comparison to the Base Case in terms of tCO_2e, and includes ±40% variability for embodied results and ±20% variability for operational results. Results for both Melbourne (Melb) and Gold Coast (Gold C) results have been provided.

Initial embodied greenhouse gas emissions (IEGHGE)

After using the Patch Exchange Hybrid method to calculate the initial embodied energy (IEE), which was then converted to initial embodied GHGE (IEGHGE), of various insulations scenarios for the case study building, it was found that from an IEGHGE perspective, only one option resulted in a decrease for both Melbourne and Gold Coast, namely straw insulation. This is due to the lower embodied energy coefficient associated with straw compared to EPS and glasswool. All other options resulted in an increase in IEGHGE, with EPS (the most energy intensive insulation material assessed) having the highest increase of almost 20 tCO_2e. The IEGHGE for all Gold Coast options are lower than that for Melbourne due to the following two factors: Gold Coast uses the black coal (which has a lower GHGE factor than Melbourne's Brown coal) and the price of goods are on average 7% lower in Gold

Coast (compared to Melbourne) (Numbeo, 2017) which has an impact on the price of the building and price of the materials which in turns lowers the IEGHGE. From an IEGHGE perspective, it appears that the most ideal solution is straw insulation, for both locations.

Recurrent embodied greenhouse gas emissions (REGHGE)

There is no recurrent embodied GHGE (REGHGE) as it is assumed the insulation has a MSL as long as the building's lifetime (Rauf, 2015).

Operational greenhouse gas emissions (OGHGE)

After using Green Building Studio to simulate the expected operational energy which was then converted to operational GHGE (OGHGE) it was found that, from an OGHGE perspective, all options lead to a decrease in GHGE. For Melbourne R3 wall insulation achieves the greatest OGHGE reduction with almost a 30 tCO_2e reduction. While for Gold Coast, the ceiling upgrades of R5 and R6 provide a much greater OGHGE reduction (compared to Melbourne ceiling results). Based only on OGHGE, for Melbourne, R3 insulation would appear to be the most ideal solution, whereas R6 ceiling insulation would appear to be more suitable for Gold Coast.

Life cycle greenhouse gas emissions (LCGHGE)

After the IEGHGE, REGHGE and OEGHGE was combined for a 50 year POA, it was found that from a life cycle GHGE (LCGHGE) perspective, all options except EPS, lead to a decrease in LCGHGE with R3 wall insulation achieving the greatest reduction for Melbourne and R6 ceiling insulation the greatest reduction for Gold Coast. The LCGHGE for Melbourne's R5 and R6 are barely visible on the graph due to the very minimal reduction of only 1 tCO_2e achieved by each (which can be attributed to the minimal impact these two options have for this location, based on the OGHGE results).

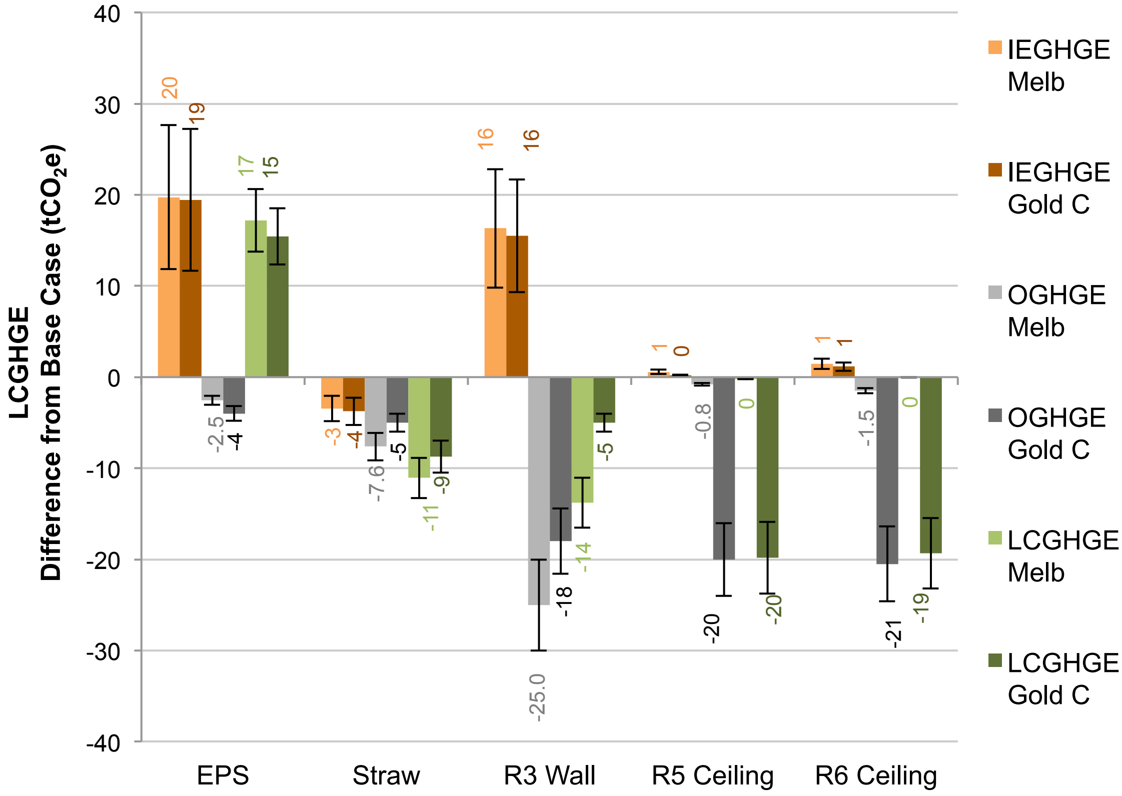


Figure 5.5 Life cycle greenhouse gas emissions breakdown for residential insulation scenarios for 50-year period of analysis for Melbourne and Gold Coast

[GHGE: Greenhouse gas emissions, IEGHGE: Initial embodied, OGHGE: Operational GHGE, LCGHGE: Life cycle GHGE, Melb: Melbourne, Gold C: Gold Coast]

This section provided an example of the type of LCGHGE results that can be achieved by using the developed framework. It also demonstrated how the individual results for each life cycle stage could be further broken down (for additional detail) and provided an example of the possible graphical output. The results in the figure above provided an example of a comprehensive approach to environmental building performance evaluation. Life cycle stages are included (other than end of life stages due to limited amount of available data), multiple upstream impacts taken into account (with the use of the hybrid approach) and it demonstrated the vital importance of analysing building design options from a life cycle perspective. It is important to bear in mind that a building design option that performs better in one life cycle stage can be detrimental to another life cycle stage. It also demonstrated how vital contextual characteristics are to LCGHGE, as various options perform better in different locations. The next section provides a breakdown of the LCC results.

Life cycle cost results

The quantification techniques described in Chapter 3 (refer to Equations 3.12 to 3.15) were used for this section. Refer to Table 5.1 for a detailed description of the insulation scenarios tested. Figure 5.6 illustrates the LCC breakdown of the insulation scenarios in comparison to the Base Case in terms of AUD 2017. Results for both Melbourne (Melb) and Gold Coast (Gold C) have been provided.

Initial cost

All insulation scenarios result in an increase in initial cost, due to the use of more materials, such as improving the R2 wall insulation to R3 or improving the R4 ceiling insulation to R5 and R6, and the use of more expensive materials such as EPS and straw. As expected the initial cost for all options is lower for Gold Coast (the average price of goods being about 7% less than Melbourne). For both Melbourne and Gold Coast, R5 ceiling insulation has the lowest initial cost compared to the other insulation options. This can be attributed to the fact that the total square meters for the ceiling is much lower than for the walls (which will require much more insulation and thus lead to an increase in initial cost).

Replacement cost

There is no replacement cost as the MSL of insulation is assumed to be the lifetime of the building.

Operational cost

After the operational cost was calculated as per the NPV equation for the 50 year POA, it was found that all options lead to an operational cost decrease, albeit quite minimal when compared to the initial cost increase. R3 wall insulation provides the greatest reduction in operational cost for Melbourne, while R6 ceiling insulation provided the greatest reduction for Gold C (echoing the OGHGE results discussed before).

Life cycle cost

After the initial, replacement and operational costs were combined as per the NPV equation, it was found R3 wall insulation is the only option results in to a decrease in LCC for the Melbourne location, due to the combined fact that it achieves the greatest operational cost reduction and has a reasonable small initial cost increase. For Gold Coast both R3 wall and R5 and R6 ceiling insulation provide a decrease in LCC, with R6 ceiling insulation achieving the greatest LCC reduction.

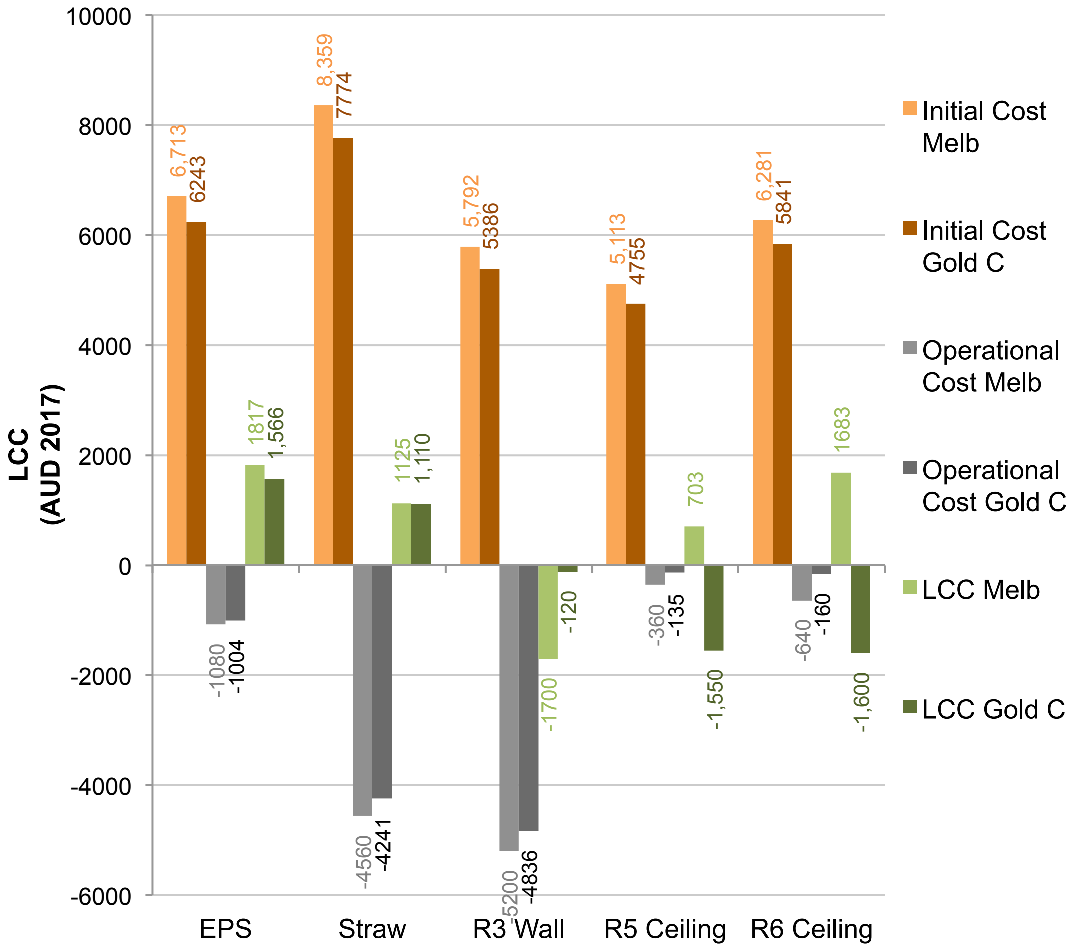


Figure 5.6 Life cycle cost breakdown for residential insulation scenarios for 50-year period of analysis for Melbourne and Gold Coast

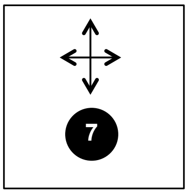
[LCC: Life cycle cost, Melb: Melbourne, Gold C: Gold Coast]

Based on an initial cost perspective (which is the basis of most design decisions), R5 ceiling insulation leads to the lowest initial cost increase, but resulted in an increase in LCC over the 50-year POA for Melbourne. For Gold Coast R5 ceiling insulation provides the lowest initial cost but R6 ceiling insulation provides the greats LCC reduction over a 50-year POA. Therefore, emphasising the critical importance of assessing building's economic performance from a life cycle perspective.

This section also provided an example of the LCC results that can be achieved by using the framework's comprehensive NPV approach (which takes the time value of money into account) and the type of graphical outputs that can be used.

A comparison of this study's LCGHGE and LCC results to other studies is provided in Section 5.5 to demonstrate that the framework provides comparable results.

5.3.1.7. Step 7: Integrate life cycle greenhouse gas emissions and life cycle cost results



The next, and most critical step, is to integrate the LCGHGE and LCC results, as per the methods described in Chapter 3 (see Section 3.2.8 and 3.2.9) and Chapter 4 (see Section 4.2.3.7). This integration helps to demonstrate the relationship and trade-offs between the economic and environmental aspects relating to building design more clearly and aids the selection process of the most suitable insulation option. This section forms a vital part of the integrated framework as most previous studies presented environmental and economic performance analysis in isolation, whereas this framework aims to show these results in an integrated manner.

Figure 5.7 provides the integrated LCGHGE and LCC results for the insulation scenarios for both Melbourne and Gold Coast locations. The x-axis provides the LCGHGE results while the y-axis provides the LCC results. The results fall within 4 quadrants (Q). Results in Q1 represent an increase in LCGHGE and LCC; while results in Q2 represent an increase LCGHGE and decrease in LCC, results in Q3 represent a decrease in LCGHGE and LCC and results in Q4 represent a decrease in LCGHGE and increase in LCC (all compared to the Base Case).

For Melbourne, both straw insulation and R3 wall insulation provide a significant LCGHGE reduction, in comparison with the Base Case, with results appearing in Q3 and Q4. However only one option, R3 wall insulation, falls within Q3 (i.e. both a LCGHGE and a LCC decrease can be expected). Based on an integrated LCGHGE and LCC perspective, R3 wall insulation is appears to be the more suitable solution (whereas R5, for example, was better from only an initial cost perspective and straw from only an IEGHGE perspective).

For Gold Coast, straw and R3 wall insulation along with R5 and R6 ceiling insulation provide a decrease in LCGHGE. However, similar to Melbourne, straw (due to its higher initial cost) leads to an increase in LCC. R3 wall insulation, R5 and R6 ceiling insulation provides a reduction in both LCGHGE and LCC (due to the improved operational performance), with R6 resulting in both the greatest LCGHGE and LCC reduction, when compared to the Base Case.

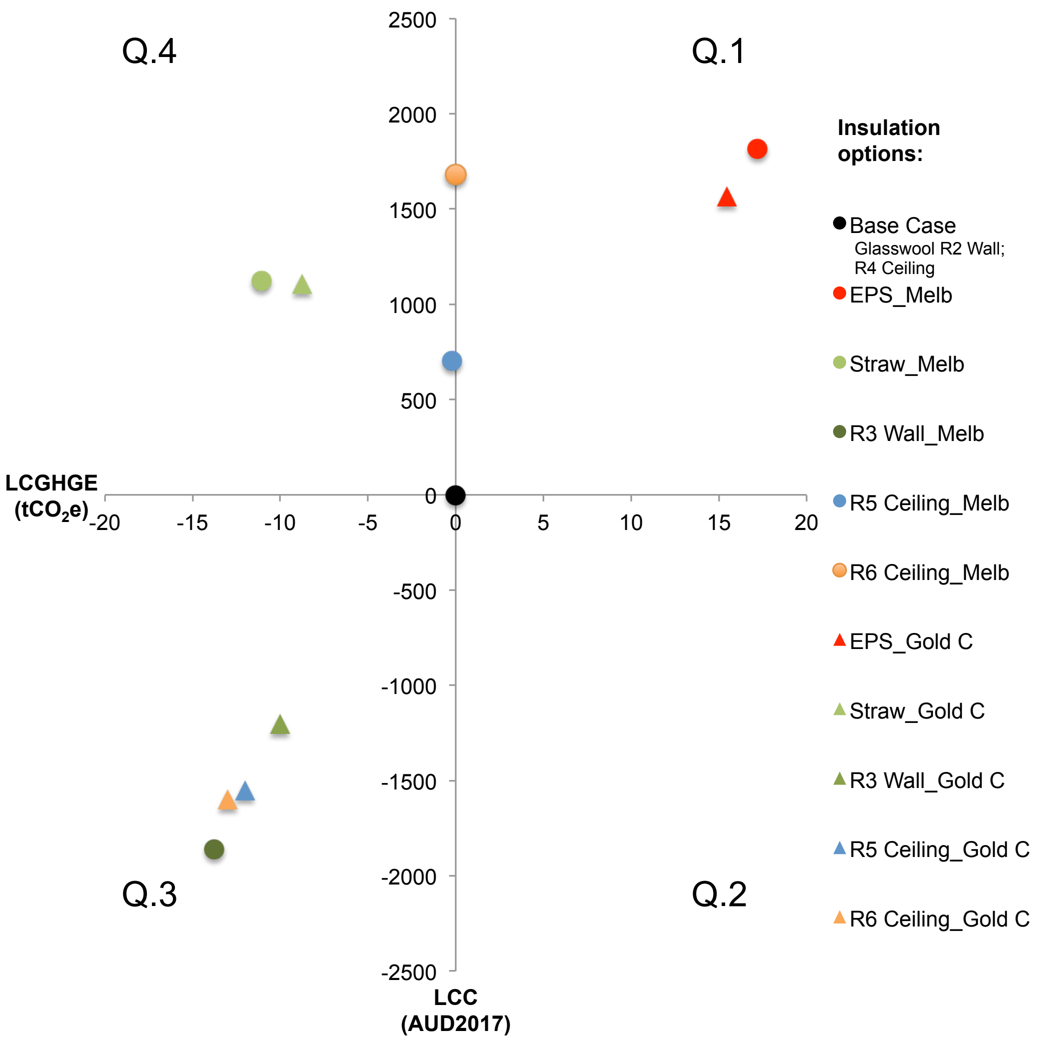


Figure 5.7 Integrated LCGHGE and LCC for residential insulation scenarios (in comparison to Base Case)

[GHGE: Greenhouse gas emissions, IEGHGE: Initial embodied, GHGE OGHGE: Operational GHGE, LCGHGE: Life cycle GHGE, LCC: Life cycle cost, Melb: Melbourne, Gold C: Gold Coast, Q: Quadrant]

[Q1: Increase in both LCC and LCGHGE; Q2: Decrease in LCC, increase in LCGHGE; Q3: Decrease in both LCC and LCGHGE, Q4: Increase in LCC, decrease in LCGHGE]

In order to gain a greater understanding of the integrated results, the LCC for each option has been divided by the tCO_2e reduced, as illustrated in Figure 5.8. The most expensive insulation option to reduce 1 tonne of CO_2e is R6 ceiling insulation for Melbourne (due to the fact that it does not achieve such a great overall LCGHGE reduction). The most cost effective option is R3 wall insulation, having a negative cost of –AUD750 for every tonne of CO_2e reduced for the Melbourne location. It is interesting to note that for Melbourne straw insulation, it is only expected to cost the user AUD100 per tonne of CO_2e reduced (which is far lower than other options such as R5 and R6 ceiling insulation). The final selection of the building element will be based on the amount the user is willing to pay for LCGHGE reduction. For Gold Coast, both R5 and R6 ceiling insulation provide a negative cost per tonne of CO_2e reduced, -AUD129 and -AUD123 respectively. EPS has not been included in Figure 5.8, as it does not lead to a decrease in LCGHGE.

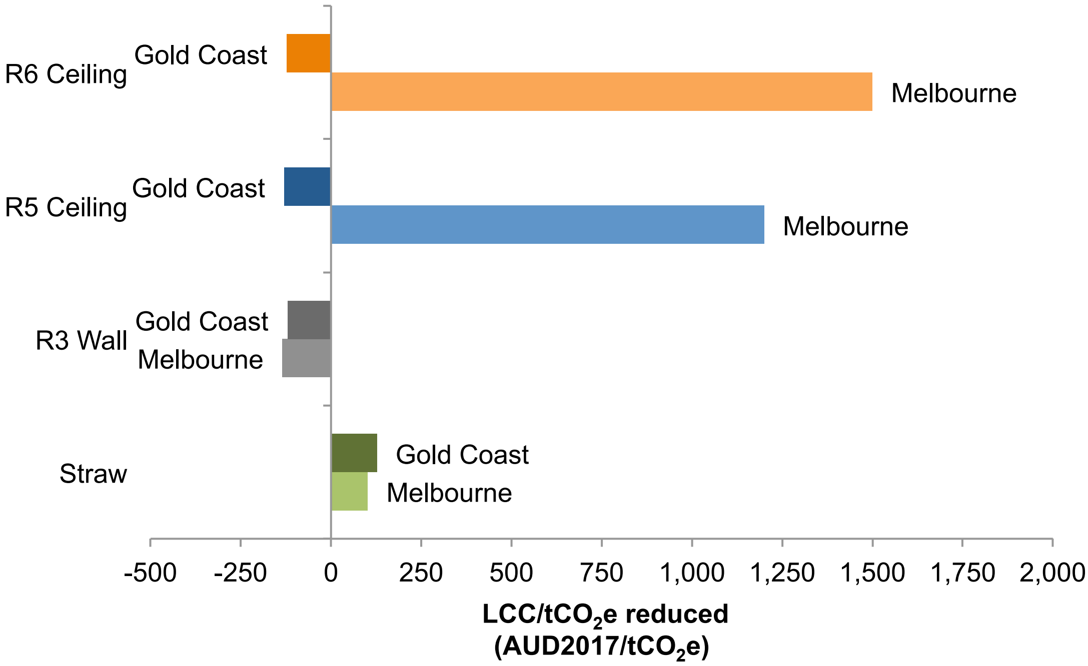
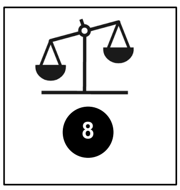


Figure 5.8 Life cycle cost/life cycle greenhouse gas emissions reduced for residential insulation scenarios, compared to Base Case

This section demonstrated how the framework could aid the integration of LCGHGE and LCC results. The use of graphical outputs such as the scatter plot provides a single graphic that incorporates both the economic and environmental factors and clearly demonstrates the possible trade-offs between these two factors. One insulation option may lead to a decrease in LCC but may result in to an increase in LCGHGE, for example. This section also demonstrated how the decision-making process can be guided by the inclusion of not only both these factors but also the life cycle perspective. This has been further elaborated upon in Chapter 6.

5.3.1.8. Step 8: Interpret findings and perform a sensitivity analysis



The second last step requires the user to interpret the results and perform a sensitivity analysis. It has been demonstrated that life cycle cost and GHGE studies suffer from a significant level of uncertainty (Islam et al., 2015a) as it is impossible to predict how the energy mix, technological improvements, price of goods, discount rate, inflation and data will change over the expected POA. In order to test the sensitivity of the results of the framework is to the various uncertainties surrounding life cycle studies, a sensitivity analysis was conducted on the Melbourne results. This is to ensure that the framework provides reliable and usable results and that it can withstand known factors that often cause variation in LCGHGE and LCC analyses.

Table 5.6 provides a summary of the sensitivity parameters tested in this section. This includes different POA, different DR, different price of goods (POG) and variability associated with the embodied and operational GHGE results, namely ±20% and ±40% (Min and Max GHGE). Refer to Chapter 3, Table 3.9 for further detail about the sensitivity parameters.

Table 5.6 Sensitivity parameters tested for case study insulation scenarios

Scenario	Detail	Scenario	Detail	Scenario	Detail
S1	POA 100 years	**S2**	Original result	**S3**	Max GHGE (+20% OE, +40% EE)
S4	Min GHGE (+20% OE, +40% EE)	**S5**	POA 20 years	**S6**	POG -40%
S7	POG -30%	**S8**	POG -20%	**S9**	POG -10%
S10	DR 3%	**S11**	POG +10%	**S12**	POG +20%
S13	POG +30%	**S14**	POG +40%	**S15**	DR 10%

Figure 5.9 illustrates the results based on the sensitivity parameters tested for the insulation scenarios. The shaded areas represent the possible range of results and the minimum (min) and maximum (max) values for both LCGHGE and LCC are provided. The sensitivity analysis was only carried out for the Melbourne case study results (as it is assumed that the Gold Coast options would follow a similar pattern).

For all options, the maximum LCGHGE reduction is achieved when the POA is increased from 50 years to 100 years. This is due to the fact that the building has a longer time to pay back its IEGHGE with the OGHGE savings. The minimum LCGHGE reduction is achieved when the POA is set to 20 years. Therefore, not allowing enough time for the building to pay back its IEGHGE. This emphasises the importance of the POA in life cycle studies. Straw insulation is the only option which consistently provides LCGHGE reduction, regardless of the sensitivity parameter selected (as all results appear in Q4). In comparison to this, EPS is the only option to consistently provide an increase in LCGHGE, regardless of the sensitivity parameter selected (as all results appear in Q1). R3 wall insulation and R5 and R6 ceiling insulation can possibly result in an increase in LCGHGE when the POA is 20 years, for example, providing less reassurance to the user of their LCGHGE reduction potential.

The maximum and minimum LCC is achieved when the DR is set to the higher value of 10% and the lower value of 3% (for all the glasswool items, i.e. R3 wall insulation, R5 and R6 ceiling insulation) respectively. For the more expensive items, such as straw and EPS, the maximum and minimum LCC is when their POG increases or decreases by ±40% (however DR has the greatest influences on the LCC results). R3 wall insulation is the only option to consistently provide a negative LCC compared to the Base Case (as all results are in Q3 and Q2), therefore providing the user with more reassurance as this insulation scenario's financial savings potential. EPS's LCC results are consistently in Q1, consequently most likely to result in increased financial cost to the user regardless of sensitivity parameters.

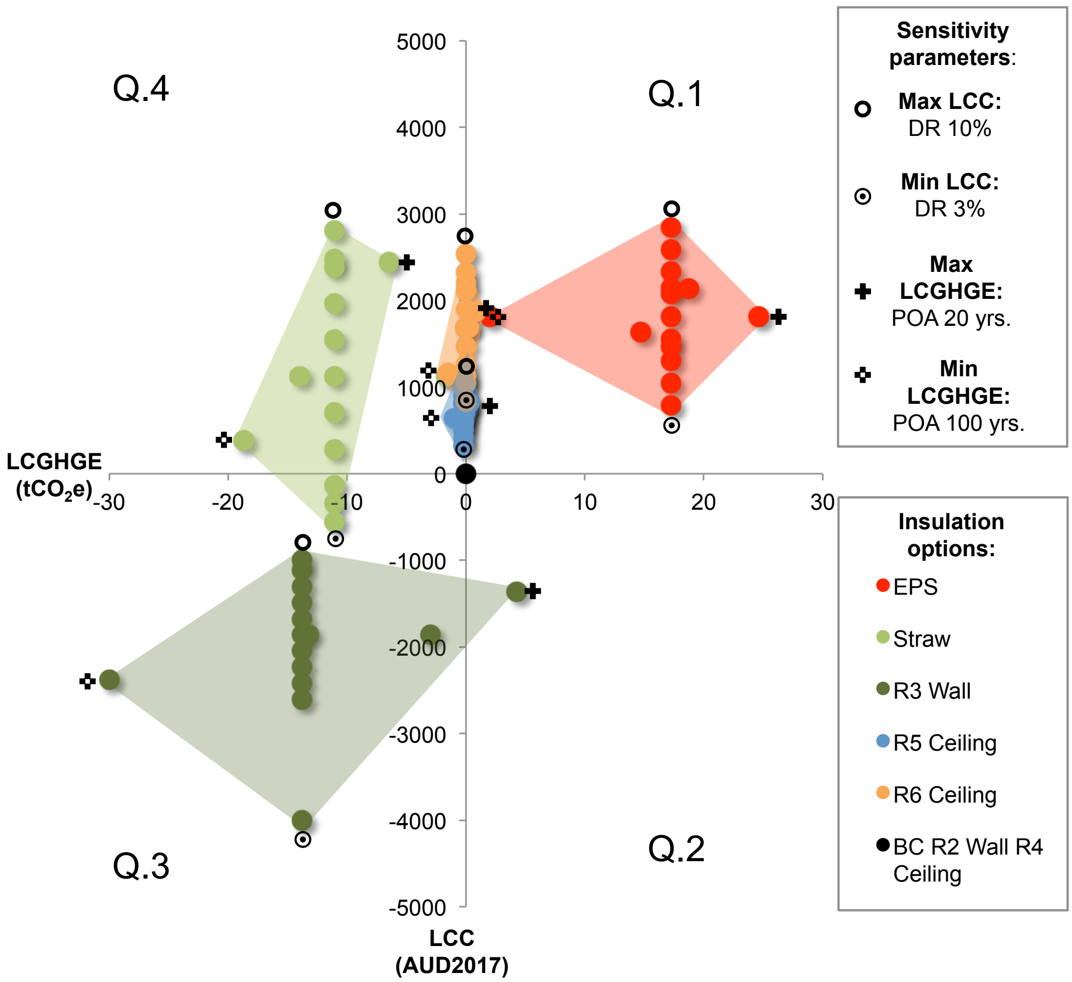


Figure 5.9 Sensitivity analysis for residential insulation scenarios

[Max: maximum, Min: minimum, LCGHGE: Life cycle greenhouse gas emissions, LCC: Life cycle cost, POA: Period of analysis, DR: Discount rate, POG: Price of goods]

Table 5.7 provides the data used for Figure 5.9, for further reference. The minimum and maximum values have been highlighted accordingly.

Table 5.7 Sensitivity analysis results for residential insulation scenarios

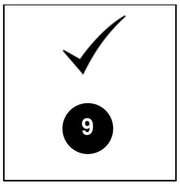
Sensitivity parameter	EPS		Straw		R3 Wall		R5 ceiling		R6 ceiling	
	LCGHGE	LCC	LCGHGE	LCC	LCGHGE	LCC	LCGHGE	LCC	LCGHGE	LCC
Original results (DR 6%, POA 50 yrs)	17.2	1816.6	-11.1	1124.8	-13.8	-1861	-0.2	702.6	0.0	1683.0
3% DR 2% IR	17.2	792.0	-11.1	-558.0	-13.8	-4000	-0.2	319.0	0.0	832.0
10% DR 3% IR	17.2	2841.0	-11.1	2807.0	-13.8	-1000	-0.2	1087.0	0.0	2535.0
Min GHGE	18.7	2134.1	-6.5	2439.9	4.3	-1361	0.3	812.4	0.9	1873.3
Max GHGE	14.7	1637.9	-14.0	384.8	-13.1	-2381	-1.0	640.9	-1.5	1168.0
POA 20 years	24.6	1816.6	-1.7	1124.8	-3.0	-1861	-0.1	702.6	3.0	1683.0
POA 100 years	3.5	1816.6	-18.7	1124.8	-30.0	-1861	-0.5	702.6	-0.1	1683.0
POG +10%	17.2	2073.0	-11.1	1544.4	-13.8	-1674	-0.2	798.6	0.0	1896.1
POG -10%	17.2	1561.0	-11.1	704.1	-13.8	-2047	-0.2	606.7	0.0	1470.3
POG +20%	17.2	2329.0	-11.1	1966.1	-13.8	-1488	-0.2	894.6	0.0	2108.9
POG -20%	17.2	1304.0	-11.1	283.4	-13.8	-2233	-0.2	510.7	0.0	1257.4
POG +30%	17.2	2585.0	-11.1	2386.8	-13.8	-1302	-0.2	990.6	0.0	2321.8
POG -30%	17.2	1048.0	-11.1	-137.3	-13.8	-2419	-0.2	414.7	0.0	1044.5
POG +40%	17.2	2830.0	-11.1	2700.0	-13.8	-1116	-0.2	1086.6	0.0	2400.0
POG -40%	17.2	794.0	-11.1	-400.0	-13.8	-2605	-0.2	325.0	0.0	900.0

Legend
- (green) Minimum value
- (red) Maximum value

The sensitivity analysis illustrates the importance of selecting an appropriate and realistic POA for LCGHGE studies, as it has a major influence on the results. The analysis further highlights how critical the DR and POG is in LCC studies, as they have a major influence on the LCC value. These factors will be discussed further in the next chapter.

This section demonstrated how a sensitivity analysis can be conducted on the integrated results, and the type of graphical devices that can be used to aid this visualisation of this sensitivity (the shaded scatter plot used in this example). It also identified additional aspects, such as the importance of the DR and POA, that have to be taken into account in future framework development, as discussed in the next chapter.

5.3.1.9. Step 9: Select appropriate option



The last step in the integrated analysis requires the user/assessor to select the most appropriate option. This step was one of the key weaknesses of previous studies, as results were not based on the user's personal preferences because they were provided in a weighted manner.

Based on the sensitivity analysis, straw insulation consistently reduced the LCGHGE regardless of the sensitivity parameter selected. However, the same option also has an increased possibility of having a positive LCC (if the POG increases or a higher DR is selected). With increasing advances in straw bale construction, with the introduction of prefabricated panels for example, which decrease construction time (thus saving expensive labour often associated with straw construction) and with increased quality (Walker, 2015), the price of straw as an insulation product, is most likely to decrease, instead of increase, in the future.

As for the high DR, several Australian sources use 10% for their 'high DR" scenario (Infrastructure Australia, 2016; Department of the Prime Minister and Cabinet, 2016; Australian Transport, 2017), with one study suggesting the use of 14% (which refers in their study to a scenario of a personal loan offered by Australia's Big Four banks) (Australian Energy Council, 2016). Even though a high DR is not assured, it is possible and could end up costing the user more for straw insulation. If the user is more concerned about the cost aspect, R3 wall insulation consistently ensures a negative LCC regardless of the sensitivity parameter selected.

However, R3 can result in an increase in LCGHGE if the POA is set to 20 years. An Australian study completed in 2013 showed that the typical buyer of a single family home can be expected to stay approximately 13 years before moving out, which is even lower than the 20 years used in this study's analysis. The most recent 'moving house' survey completed by ABS states that on average people move every 15 years (which is again lower than this study), and that young households without children move the most frequently whilst older couples without children stay in their houses longer (Australian Bureau of Statistics, 2011).

The type of owner or developer can severely influence the expected POA and in consequence the overall results. For example, a younger couple will more than likely move within 20 years, therefore the option of R3 wall insulation will not be an ideal solution as they will move out of the house before they can benefit from reduced LCGHGE. An older couple will potentially have a greater prospect of staying in the house for more than 20 years, increasing the probability of benefitting from reduced LCGHGE. A recent study in the USA states that owning a house for 40 to 50 years is no longer the norm, and that 10 years has become the new norm (Nelson, 2016). The shorter POA potentially produces more realistic results, suggesting that R3 wall insulation is not the most ideal solution from a LCGHGE perspective.

However, the 'appropriate' selection will depend on the user. If they prefer to select something where they are more assured of a LCGHGE reduction, then straw insulation would be most ideal. If cost is a major concern then R3 wall insulation would be better, bearing in mind that a longer POA will be more favourable.

5.3.2. Glazing scenario results

In order to demonstrate that the integrated framework can be applied to various forms of building design related decisions, another building element, namely glazing, was used to demonstrate the framework. The framework approach, discussed in Chapter 4, has been applied to the same residential building case study (and two different locations) used in the previous section and adapted to specific glazing scenarios, as illustrated in Figure 5.10. Each step has been further explained below.

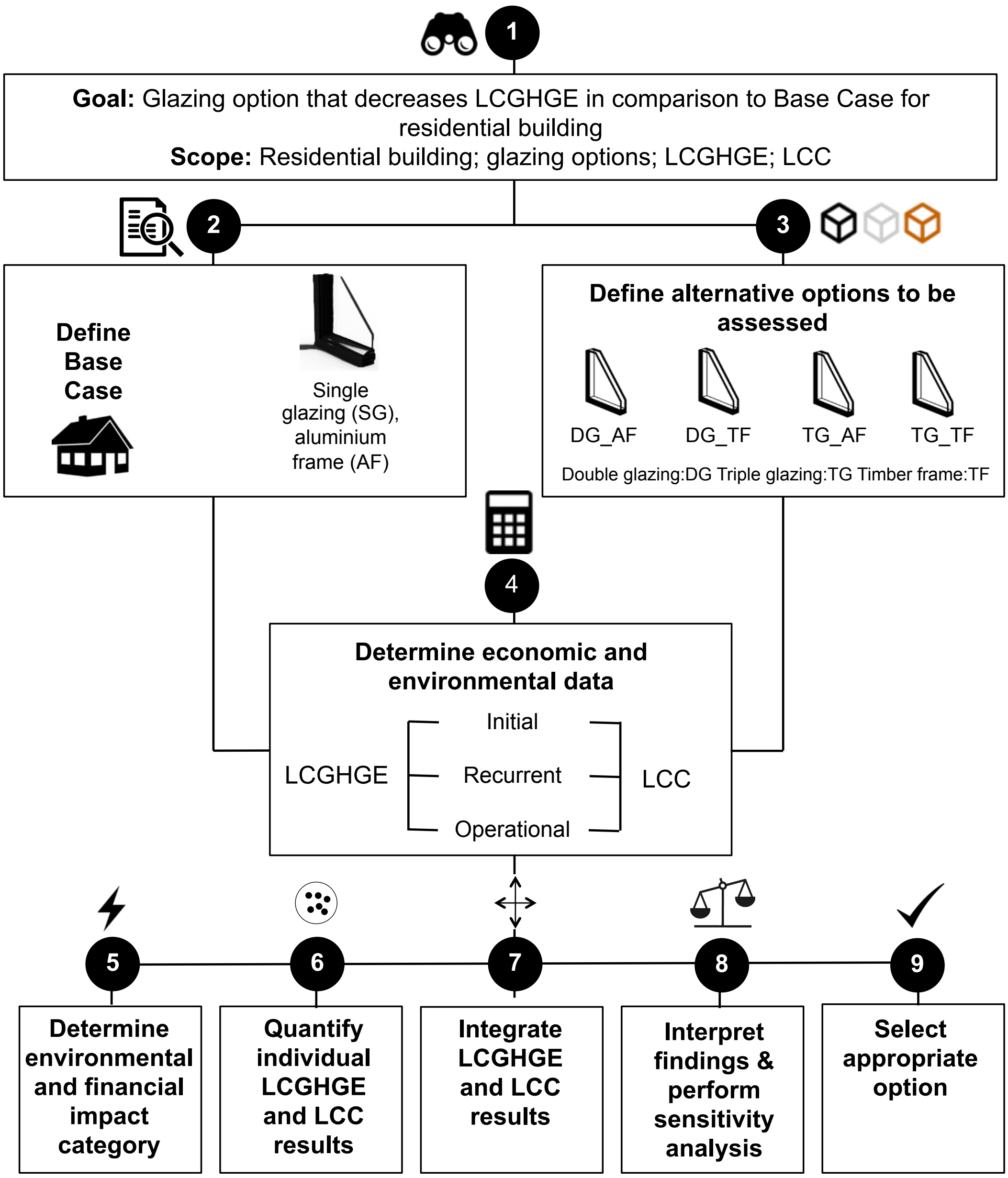
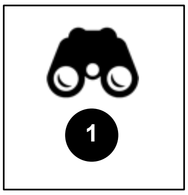


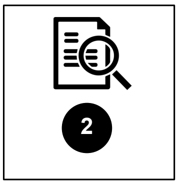
Figure 5.10 Framework approach for residential glazing scenario analysis

5.3.2.1. Step 1: Define the goal and scope of the assessment



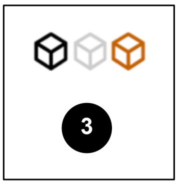
The goal of the assessment is to determine which glazing option results in a decrease in the building's LCGHGE when compared to the Base Case and to assess the LCC implications of these glazing scenarios. The scope of the assessment is similar to that of the insulation assessment (see Section 5.3.1.1).

5.3.2.2. Step 2: Define the Base Case



For Step 2 the Base Case is the glazing provided as part of the residential case study building, as described in Chapter 4. According to the developer of the case study building, single glazing with an aluminium frame is the standard glazing inclusion (Metricon, 2017).

5.3.2.3. Step 3: Define alternative options to be assessed



The next step involved defining alternative glazing options that could be tested for the residential building. As stated previously (see Section 5.2.2.2), the U-Value and type of frame can significantly affect the LCGHGE performance of glazing. Therefore, different framing materials and an increase in U-Values (through additional glazing panes) have been tested, as summarised in Table 5.2.

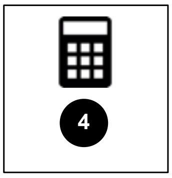
Figure 5.11 provides an example of what section of the case study's bill of quantities (as provided in Table C1 in Appendix C) is adjusted for the glazing scenario analysis (i.e. the rows corresponding to the window frame and glass type is adjusted according to each glazing scenario tested).

Component	Material	Material Quantity	Material Quantity unit	Embodied energy coefficient (GJ/unit)[1]	Wastage multiplier[1]
Foundation, ground floor					
Ground floor	Concrete slab	48.00	m^3	4.44	1.1
	Polystyrene waffle pods	40.54	m^3	7.04	1.05
	Steel reinforcement Bar	0.34	t	85.46	1.05
	Steel reinforcement Mesh	0.37	t	85.46	1.05
	Plastic membrane	229.00	m^2	0.51	1.05
External wall					
External cladding	Clay brick	165	m^2	0.56	1.05
Wall ties	Stainless Steel	0.04280	t	85.46	1.05
Insulation	Aluminium Reflective foil	134	m^2	0.14	1.1
	R2 Fibreglass insulation	11	m^3	2	1.1
Internal lining	Plasterboard	150	m^2	0.21	1.05
Timber framing					
Framing	Softwood	8.48	m^3	10.9	1.02
Internal wall					
Finish	Plasterboard	775	m^2	0.21	1.05
	Insulation	2.33	m^3	2	1.1
Roof					
Tiles	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Insulatio[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Frame: Rafters & ridge beams	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Purlins/ Girders	Softwood	0.38	m^3	10.9	1.02
Insulation	Glasswool ceiling batts, R4	44.00	m^3	2	1.1
Finish	Plasterboard	226	m^2	0.21	1.05
Gutter	Steel	0.021	t	0.933	1.05
Windows					
Frame	Aluminium	0.15	t	252.6	1.1
Glass	Clear	30	m^2	1.73	1.03
Doors					

Windows					
Frame	Aluminium	0.15	t	252.6	1.1
Glass	Clear	30	m^2	1.73	1.03

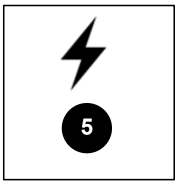
Figure 5.11 Section of the bill of quantities modified for glazing scenarios

5.3.2.4. Step 4: Determine the economic and environmental data



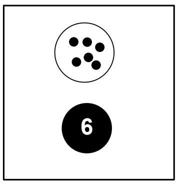
Step 4 requires the determination of economic and environmental data for the assessment. This section relates to the equations presented in Chapter 4. Environmental data is the data required to quantify LCGHGE and has been presented in Table 5.4. The economic data is the data required to quantify LCC and has been presented in Table 5.5. Refer to Appendix B for an example of the predefined inputs and Appendix C for user-defined inputs. The aim of this section is to provide an example of the type of data required to complete the LCGHGE and LCC assessment that forms part of this study's integrated assessment.

5.3.2.5. Step 5: Determine environmental and economic impact category



Step 5 requires the selection of an environmental and economic impact category. For this study, global warming potential (GWP) (tCO_2e) has been selected for the LCGHGE indicator and AUD 2017 for the LCC indicator.

5.3.2.6. Step 6: Quantify individual life cycle greenhouse gas emissions and life cycle cost results



The next step was to quantify the LCGHGE and LCC individually (before the critical step of integrating the results). The glazing options were applied to the residential building case study in order to determine which option provides the greatest reduction in LCGHGE compared to the Base Case and to gain an understanding of the LCC implications of this reduction. First the LCGHGE results are discussed followed by the LCC results. The aim of this section is to provide an example of LCGHGE and LCC results that can be achieved by the quantification techniques (namely Path Exchange hybrid approach and NPV approach) selected in Chapter 3.

Life cycle greenhouse gas emissions results

Figure 5.12 illustrates the LCGHGE results and includes ±40% variability for embodied GHGE results and ±20% variability for operational results. Results for both Melbourne (Melb) and Gold Coast (Gold C) have been provided.

Initial embodied greenhouse gas emissions (IEGHGE)

After using the Patch Exchange Hybrid method to calculate the initial embodied energy (IEE), which was then converted to initial embodied GHGE (IEGHGE), of various glazing scenarios for the case study building, it was found that for all scenarios the IEGHGE increases (due to more material use) except for the SG_TF option, as timber is a less energy intensive material to use for the frame than the Base Case aluminium frame. Similar to the insulation findings, the IEGHGE for all Gold Coast options are lower than that for Melbourne due to the use of black coal and the lower price of materials (refer to Section 5.3.7.1 for more detail). For both Melbourne and Gold Coast, SG_TF would be most suitable from an IEGHGE perspective.

Recurrent embodied greenhouse gas emissions (REGHGE)

In contrast with insulation, glazing is not expected to last the building's service life for this study and depending on the type of frame, must be replaced over the 50-year POA. There is an increase in REGHGE for all the options, with TG_TF resulting in the greatest increase of approximately 18 tCO_2e (in comparison to the Base Case). This is due to the fact that this glazing option has the highest initial cost and is thus quite costly to replace (which in turns increases the REGHGE). For both Melbourne and Gold Coast, SG_TF appears to best from a REGHGE perspective.

Operational greenhouse gas emissions (OGHGE)

After using Green Building Studio to simulate the expected operational energy (which was then converted to operational GHGE (OGHGE), it was found that all options lead to a decrease in OGHGE as all glazing options represent more energy efficient alternatives than the Base Case SG_AF (due to either improved frame material selection or better thermal performance with the additional glass panes). The greatest reduction in OGHGE is achieved for the TG_TF option with a reduction of roughly 206 tCO_2e for Melbourne and 150 tCO_2e for Gold Coast, appearing to be the best solution from an OGHGE perspective.

Life cycle greenhouse gas emissions (LCGHGE)

After the IEGHGE, REGHGE and OEGHGE were combined for a 50 year POA, it was found that from a life cycle GHGE (LCGHGE) perspective all options similarly result in a decrease in LCGHGE, which is due to the improved operational performance, with the greatest reduction achieved for the TG_TF options. Melbourne has a reduction of approximately 180 tCO_2e and Gold Coast approximately 129 tCO_2e. Based on a LCGHGE perspective, the glazing option of TG_TF appears to be the best solution for this particular case study.

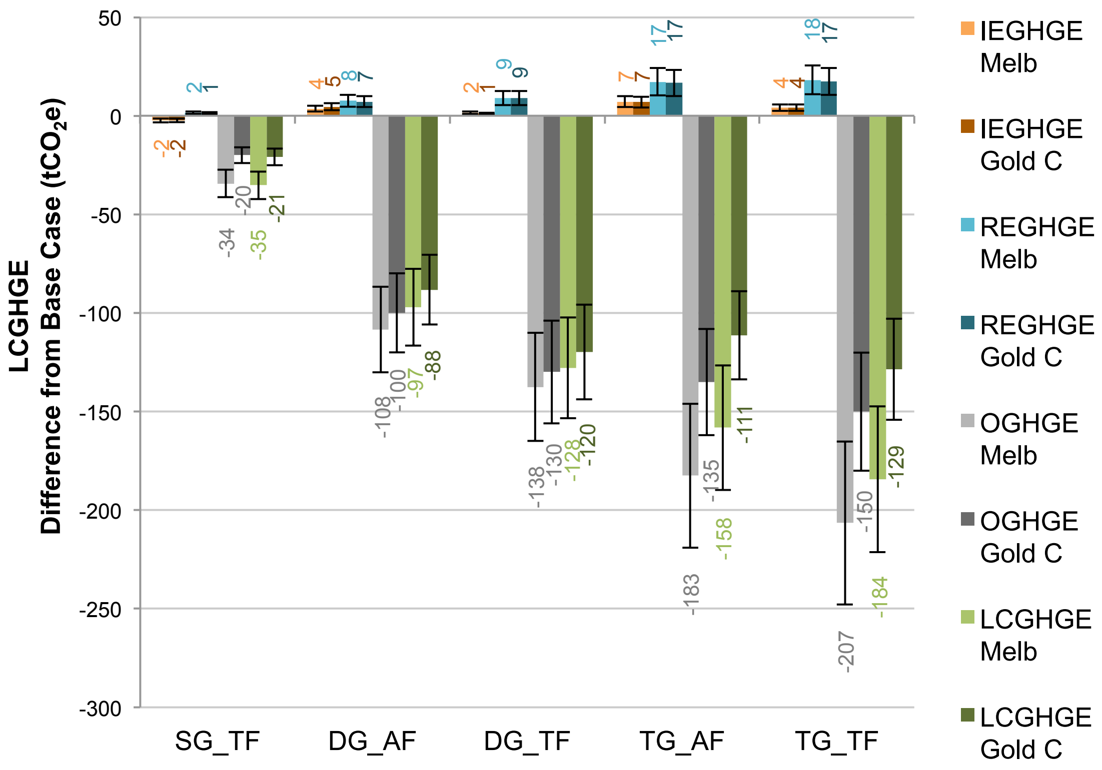


Figure 5.12 Life cycle greenhouse gas emissions breakdown for residential glazing scenarios for 50-year period for Melbourne and Gold Coast

[SG: Single glazing, DG: Double glazing, TG: Triple glazing, AF: aluminium frame, TF: Timber frame Melb: Melbourne, Gold C: Gold Coast]

This section helped to illustrate the importance of analysing building related design decisions from a life cycle perspective. It also provided an example of how the framework's LCGHGE quantification approach can be applied to another building design element, other than the insulation example discussed earlier, and how specific contextual characteristics (like climate) can influence the results. The next section provides the LCC results for the glazing scenarios.

Life cycle cost results

Initial cost

Figure 5.13 provides the LCC results for the residential glazing options over the 50-year POA. All options result in an increase in initial cost compared to the Base Case (TF windows are more expensive than AF windows and DG and TG more expensive than SG). As expected, the TG_TF option has the highest initial cost. Similar to the insulation results, initial cost for all options is lower for Gold Coast (as the average price of goods is about 7% less than Melbourne). Based on an initial cost perspective, SG_TF would be the best solution for both locations.

Replacement cost

This increase in initial cost has an impact on the replacement cost (as each option is more expensive to replace than the Base Case SG_AF). However, as AF windows generally have a shorter MSL than TF windows (Rauf and Crawford, 2013), the DG_AF and TG_AF options have a higher replacement cost than their timber framed counterparts. Based on a replacement cost perspective, SG_TF would be the best solution for both locations.

Operational cost

After the operational cost was calculated as per the NPV equation for the 50-year POA, it was found that all options results in a decrease in operational cost compared to the Base Case. TG_TF achieves the greatest reduction for both locations, while SG_TF achieves the least reduction.

Life cycle cost

After the initial cost, replacement cost and operational cost were combined as per the NPV equation, it was found that the increase in initial and replacement cost and minimal operational cost savings results in an increase in LCC for the POA of 50 years for all glazing scenarios, except DG_TF. This can be attributed to the fact that the replacement cost is not as high and that there is enough reduction in the operational cost to pay back the increased initial cost. Based on a purely LCC perspective, DG_TF is the best solution for both locations.

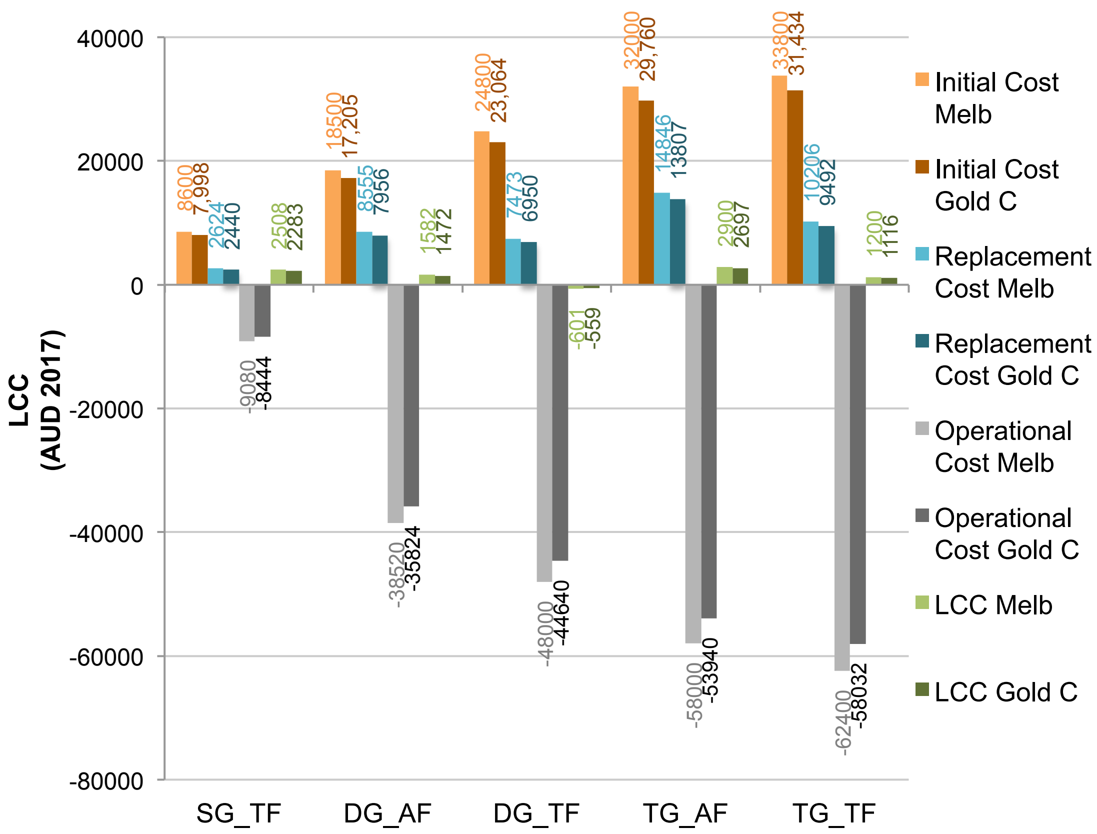


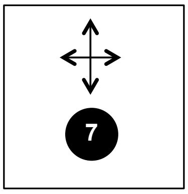
Figure 5.13 Life cycle cost breakdown for residential glazing scenarios for 50-year period of analysis for Melbourne and Gold Coast

[SG: Single glazing, DG: Double glazing, TG: Triple glazing, AF: aluminium frame, TF: Timber frame, Melb: Melbourne, Gold C: Gold Coast]

This section demonstrated, again, the importance of the life cycle perspective is to cost studies, as an option that might have a lower initial cost (the basis of most building design decisions) can actually increase the whole life cycle cost. It also demonstrated how the NPV approach for LCC quantification can be applied to successfully take the time value of money into account and help inform the final selection process.

A comparison of this study's LCGHGE and LCC results to previous studies is provided in Section 5.5, in order to ensure the framework provides comparable results.

5.3.2.7. Step 7: Integrate life cycle greenhouse gas emissions and life cycle cost results



The next and most critical step is to integrate the LCGHGE and LCC results in order to demonstrate, with greater clarity, the relationship and trade offs between these two factors and to aid the selection process of the best glazing option. Most previous studies only provide the environmental and economic results in isolation (refer to Chapter 2), similar to the results presented in Step 6, but this framework goes beyond that and aims to provide a more comprehensive form of analysis by the integration of the two aspects.

The LCGHGE and LCC results were integrated, as illustrated in Figure 5.14. Only quadrants 3 and 4 are visible as all options results in a decrease in LCGHGE (due to the improved thermal performance of the glazing options compared to the Base Case). All options, except DG_TF, fall within quadrant 4, meaning that these options decrease LCGHGE but increase LCC, with the highest LCC option being TG_AF for both Melbourne and Gold Coast (which is similar to the LCC findings discussed in Section 5.4.7.2). Only DG_TF leads to a reduction in both LCGHGE and LCC (Q3), appearing to be the ideal solution from an integrated LCGHGE and LCC perspective for both Melbourne and Gold Coast. However, this option does not result in the greatest reduction in LCGHGE, which is TG_TF. The difference in LCGHGE reduction potential between the DG_TF and TG_TF options is not as significant for the Gold Coast location as it is for the Melbourne location (which can be attributed to the colder Melbourne climate deriving greater benefit from to triple glazed windows).

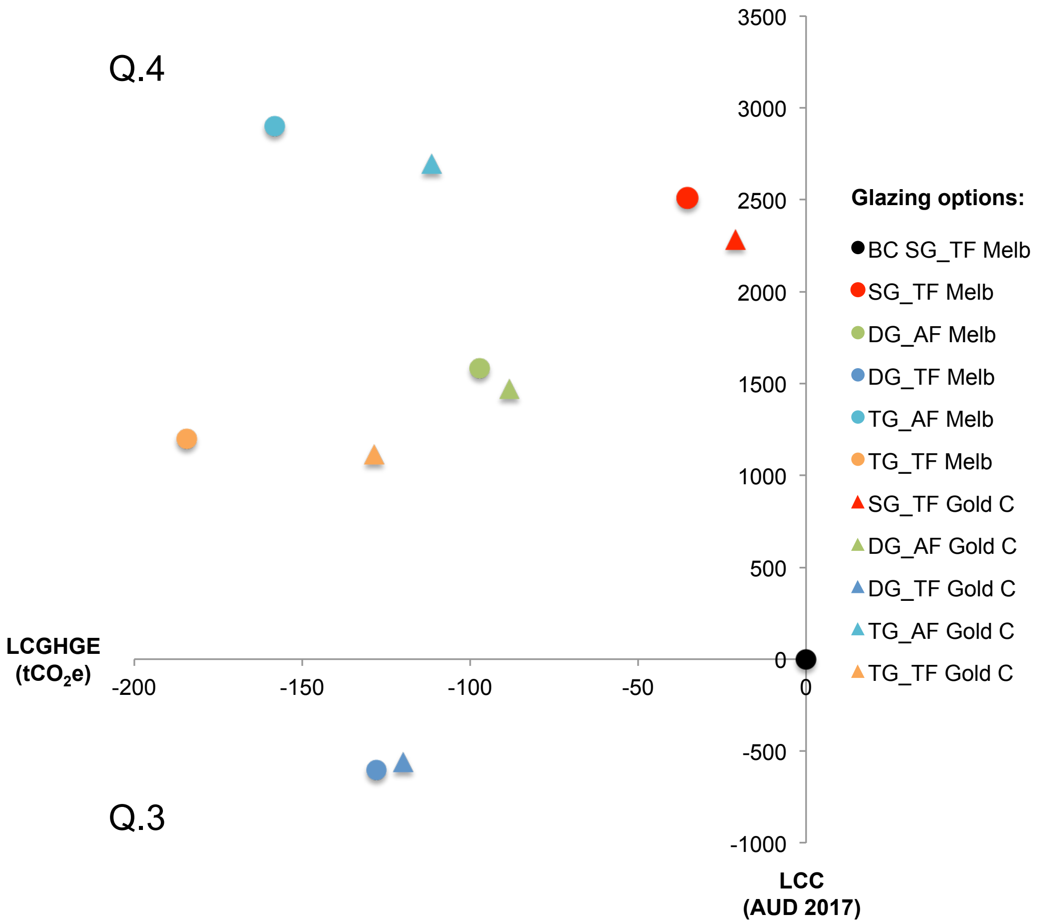


Figure 5.14 Integrated life cycle greenhouse gas emissions and life cycle cost of residential glazing scenarios for 50-year period for Melbourne and Gold Coast, compared to the Base Case

*[*SG: Single glazing, DG: Double glazing, TG: Triple glazing, AF: aluminium frame, TF: Timber frame *GHGE: Greenhouse gas emissions, IEGHGE: Initial embodied, GHGE OGHGE: Operational GHGE, LCGHGE: Life cycle GHGE, LCC: Life cycle cost, Melb: Melbourne, Gold C: Gold Coast, Q: Quadrant]*

[Q1: Increase in both LCC and LCGHGE; Q2: Decrease in LCC, increase in LCGHGE; Q3: Decrease in both LCC and LCGHGE, Q4: Increase in LCC, decrease in LCGHGE]

In order to obtain greater understanding of the integrated results, the LCC for each option has been divided by the tCO_2e reduced, as illustrated in Figure 5.15. This clearly demonstrates the fact that DG_TF is the only option that has a negative cost of roughly –AUD 5 for every tonne of CO_2e reduced for both Melbourne and Gold Coast. However, for a value of approximately AUD 5/tCO_2e reduced for Melbourne and AUD 8/tCO_2e reduced for Gold Coast, one can select TG_TF which actually results in a greater decrease in LCGHGE overall (however as stated before the difference in LCGHGE reduction between TG_TF and DG_TF is not as significant for the Gold Coast location, which can have an impact on the final selection process). Again, the final selection will be dependent on the user's personal preferences and willingness to pay for reduction of LCGHGE.

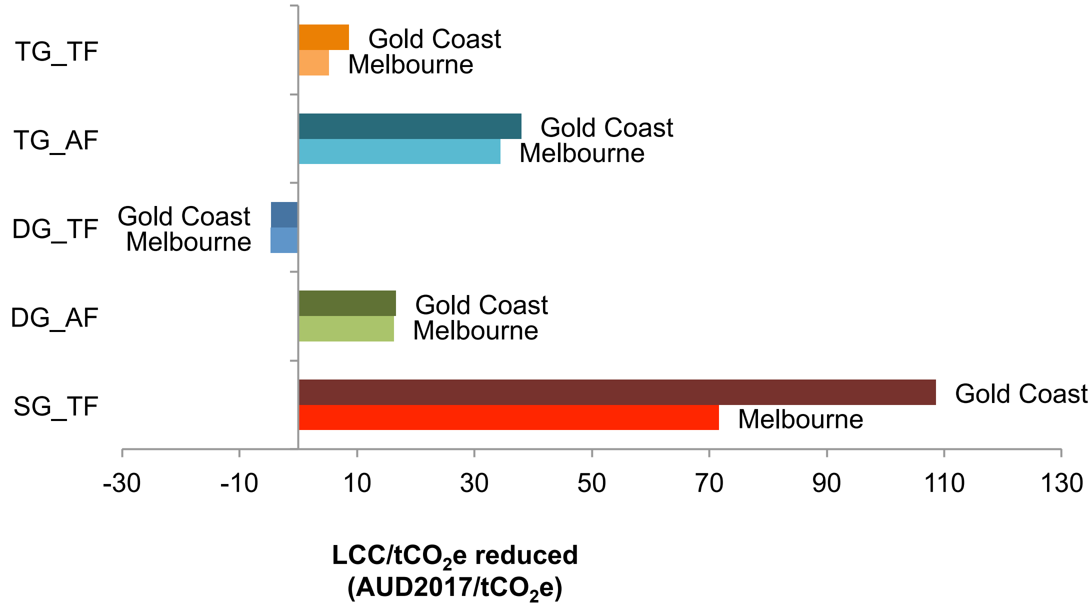
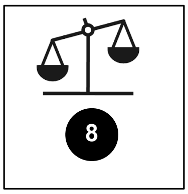


Figure 5.15 Life cycle cost/life cycle greenhouse gas emissions reduced for residential glazing scenarios, compared to Base Case

*[*SG: Single glazing, DG: Double glazing, TG: Triple glazing, AF: aluminium frame, TF: Timber frame *LCC: Life cycle cost]*

Similar to the insulation analysis, this section provided an example of how to integrate the environmental and economic building performance results and the type of graphical outputs that can be used to aid this integration process. This section also demonstrated the critical importance of looking at both the environmental and economic results simultaneously in order to better inform the final selection of the appropriate building design scenario.

5.3.2.8. Step 8: Interpret findings and perform a sensitivity analysis



Similar to the insulation study, the second last step requires the user to interpret the results and perform a sensitivity analysis, by way of the methods described in Chapter 3 (Table 3.9). The same sensitivity parameters that were tested for the insulation scenarios (Table 5.6) were used for the glazing scenarios. The sensitivity analysis was only carried out for the Melbourne case study results.

The sensitivity analysis results are illustrated in Figure 5.16. The shaded area illustrates the range of results for each glazing option. Minimum and maximum LCC and LCGHGE values are indicated with the corresponding key. Similar to the insulation results, the minimum and maximum LCGHGE is achieved when the POA is set to 20 or 100 years, respectively. This is due to the significant role that the IEGHGE plays in LCGHGE. If the POA is not long enough for the building to pay it back it will result in a minimal LCGHGE reduction (if any at all). The opposite is true for a longer POA where a greater LCGHGE reduction can be achieved. All options consistently provide a decrease in LCGHGE, regardless of sensitivity parameter (i.e. results appear in Q3 and Q4), therefore ensuring the user of the GHGE reduction potential.

The maximum LCC for glazing is influenced by its MSL (unlike insulation which did not have any replacement costs). If a lower MSL is selected (for example 15 years for AF and 25 years for TF) it increases the replacement costs, thereby increasing the LCC. However, the DR still has the greatest impact on the minimum and maximum LCC results for all options. There in no single option that either consistently results in a decrease in LCC or increase in LCC. DG_TF resulted in a decrease of LCC, can easily be influenced by factors such as DR and price of goods (POG), which increases its LCC.

What is interesting to note from the sensitivity analysis, is that regardless of which sensitivity parameters were selected, all options consistently lead to a reduction in LCGHGE. This illustrates the important role that more energy efficient glazing solutions play in residential building design. However, the selection of the preferred option is not as simple as this due to the variability in LCC results, with options such as DG_TF (the ideal solution selected in the previous section from the integrated LCGHGE and LCC perspective) resulting a potential increase in LCC. This is explored further in Figure 5.17.

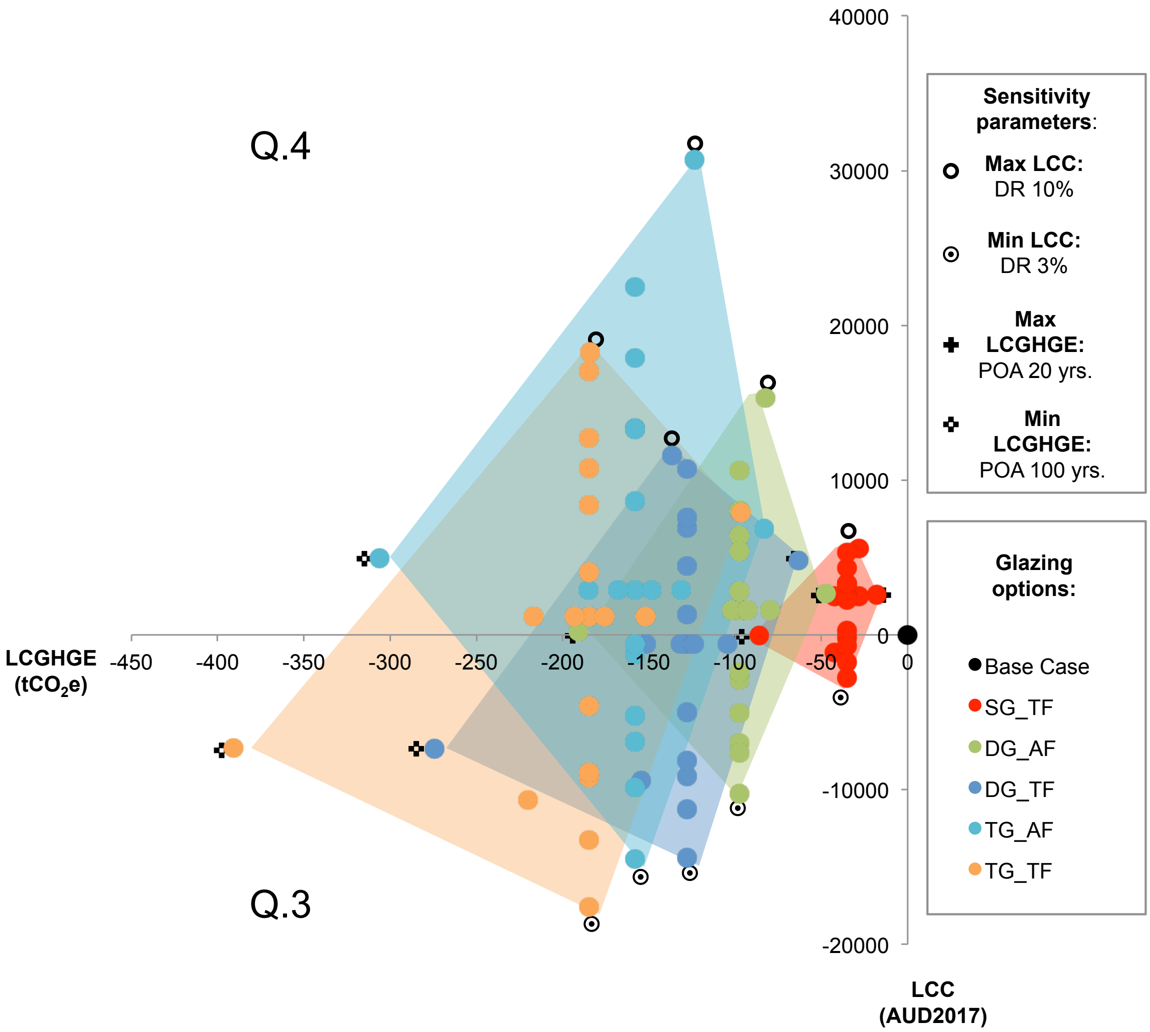


Figure 5.16 Sensitivity analysis for residential glazing scenarios

[Max: maximum, Min: minimum, LCGHGE: Life cycle greenhouse gas emissions, LCC: Life cycle cost, POA: Period of analysis, DR: Discount rate, POG: Price of goods]

Table 5.8 provides the data used for Figure 5.16, for further reference. The minimum and maximum values have been highlighted accordingly.

Table 5.8 Sensitivity analysis results for residential glazing scenarios

Sensitivity parameter	SG_TF		DG_AF		DG_TF		TG_AF		TG_TF	
	LCGHGE	LCC	LCGHGE	LCC	LCGHGE	LCC	LCGHGE	LCC	LCGHGE	LCC
Original results (DR 6%, POA 50 yrs)	-35	2508	-97	1582	-128	-601	-158	2900	-184	1200
3% DR 2% IR	-35	-2760	-97	-10263	-128	-14406	-158	-14473	-184	-17579
10% DR 3% IR	-35	5591	-97	15287	-128	11605	-158	30715	-184	18242
Min GHGE	-28	2508	-80	1582	-104	-601	-131	2900	-152	1200
Max GHGE	-42	2508	-97	1582	-151	-601	-185	2900	-217	1200
POA 20 years	-18	2608	-47	2691	-63	4793	-83	6868	-97	7896
POA 100 years	-86	-52	-191	235	-274	-7350	-306	4968	-391	-7324
Min MSL	-28	5300	-82	14285	-137	10500	-124	30600	-184	17522
Max MSL	-42	-1155	-97	-2908	-154	-9402	-158	-1289	-220	-10687
POG +10%	-35	2285	-97	2803	-128	1309	-158	8635	-184	4064
POG -10%	-35	266	-97	-2423	-128	-4977	-158	-608	-184	-4593
POG +20%	-35	3294	-97	5416	-128	4453	-158	13257	-184	8393
POG -20%	-35	-743	-97	-5037	-128	-8120	-158	-5230	-184	-8922
POG +30%	-35	4304	-97	8030	-128	7596	-158	17879	-184	12721
POG -30%	-35	-1753	-97	-7650	-128	-11264	-158	-9852	-184	-13251
POG +40%	-35	5313	-97	10643	-128	10739	-158	22501	-184	17050
POG -40%	-35	-2600	-97	-10060	-128	-12000	-158	13000	-184	16432

Legend		
	(green)	Minimum value
	(pink)	Maximum value

The LCC variability is quite apparent in Figure 5.17, with the original values (based on LCC/tCO_2e reduced) highlighted in orange, the minimum LCC in green and maximum LCC in black. For an option such as SG_TF, the LCC can be reduced as much as -80 AUD/tCO_2e compared to the Base Case, to as much as 200 AUD/tCO_2e reduced. This emphasises how critical sensitivity analysis is on life cycle studies and how important it is to communicate the best and worst case scenarios to users. What is interesting to note is that even though DG_TF does result in a worst-case scenario increase of 84 AUD/tCO_2e reduced, this option has the lowest LCC/tCO_2e reduced scenario compared to all other options. It also has the greatest reduction in LCC/tCO_2e reduced for its best-case scenario.

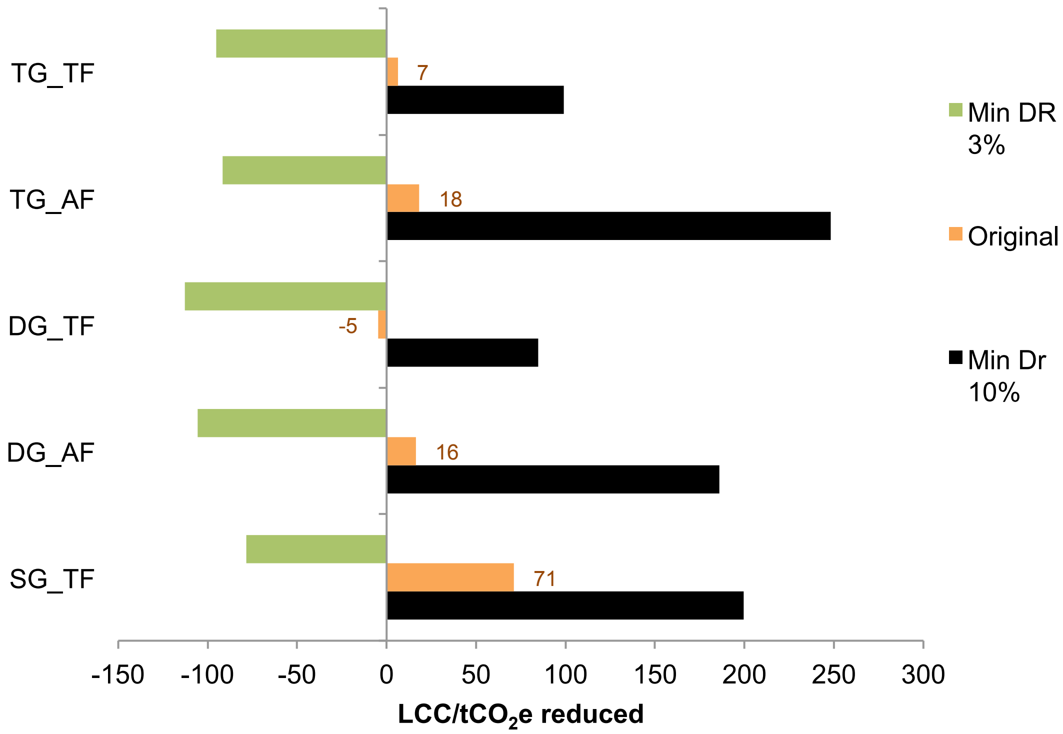
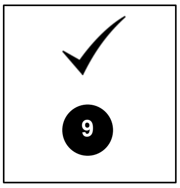


Figure 5.17 LCC variation for residential glazing scenarios (AUD 2017), compared to Base Case

These framework results emphasise how important it is to take into account parameters such as DR and POA when interpreting results.

5.3.2.9. Step 9: Select appropriate option



The last step in the integrated analysis requires the user/assessor to select the most appropriate option, an aspect often missing from previous frameworks (as personal preferences are typically not taken into account).

Based on the analysis above, all options result in a decrease in LCGHGE in comparison to the Base Case, regardless of which sensitivity parameter is selected. All options would therefore be a better selection than the Base Case option of SG_AF. For a user wishing to decrease LCGHGE and be more assured of not resulting in a drastic increase in LCC, SG_TF would appear the most appropriate option. For a user wanting to be assured of the greatest LCGHGE decrease regardless of the cost consequence: TG_TF would be the most appropriate option resulting in quite a significant LCGHGE decrease compared to the other options. For a user wishing to select an option that results in a decrease in both LCGHGE and LCC, DG_TF would be the most obvious choice.

5.4. Comparison to previous studies

In order to ensure that the framework's insulation and glazing results are within an acceptable range, and provide comparable and reliable results, the LCGHGE and LCC results were compared to similar previous studies for both the insulation and glazing scenarios. LCGHGE comparison of results is discussed first followed by LCC results comparison.

5.4.1. Comparison of insulation results to previous studies

5.4.1.1. Life cycle greenhouse gas emissions results

A summary of the framework's results and other consulted studies are provided in Table 5.9. With regard to the IEGHGE results, previous studies, including Anastaselos et al. (2009) and Tettey et al. (2014), also found EPS insulation to provide one of the highest initial embodied GHGE when compared to other less energy intensive insulation materials such as glasswool or mineral wool. In comparison, straw insulation has been demonstrated to have a lower IEGHGE (Downton, 2013) and help lower the OGHGE of a building (Garas et al., 2009), similar to that found in the case study building results within this chapter. However, Garas et al. (2009) found that using straw insulation can decrease the space heating by 20%, which is much higher than that found for this demonstration of the framework with an 8% decrease.

However, this may be due to the fact that their study utilised a much greater width of straw bale of 450mm (compared to the Base Case 140mm), which could possibly have lead to an increase in the material's thermal efficiency. It has also been found that straw insulation is better suited to colder climates, as the benefits are somewhat decreased in hot or humid climates (Geiger, 2001; Morrison, 2007). This is evident in this study as straw insulation resulted in a greater decrease in OGHGE for the Melbourne location than for the Gold Coast location.

Previous studies, such as Stephan et al. (2013), a found that increasing the R-Value (which leads to an increase in material quantities) also results in an increase in the initial energy but leads to a potential decrease in operational energy. This can be seen when increasing the case study building wall insulation R-Value from R2 to R3, which results in an increase in IEGHGE but also leads to a decrease in OGHGE. However the exact percentage in operational energy reduction varies when increasing the insulation thickness and has been demonstrated to be between 22% and 79% (Bolatturk, 2006; Hasan et al., 2008). This is considerably higher than the 10% reduction found by increasing R2 to R3 in the Base Case building, however the type of insulation and extent of its application has not been made clear in the previous studies and thus could be the reason for the different results. As stated previously, OGHGE results can vary by up to 20% (Juodis et al., 2009) and if this is factored in, the R3 insulation option can result in a maximum decrease of almost 19% which is closer to the 22% to 79% range. An Australasian study example found a OGHGE decrease of approximately 7% when varying the insulation R-Value from R2 to R3 for a dwelling in Sydney (Bambrook et al., 2011). This is quite close to the framework's results, however the different climatic conditions between Sydney (a humid subtropical climate) and Melbourne (a temperate climate), have to be considered when comparing the results. Other factors such as the ventilation rate and infiltration rate used for the operational simulation can also affect the results. Similar to this study, Inerney (2011) and Aliento (2015) also found ceiling insulation more beneficial to warmer climates, like Gold Coast than to Melbourne's climate. In hotter climates it is more important to reduce the direct radiation from the sun on the roof and have higher insulation values in the ceiling to help reduce heat gains.

Table 5.9 Comparison to previous studies for insulation LCGHGE

Insulation type	Comparison to other study and location		This study: Melbourne results	This study: Gold Coast results
EPS	EPS has a 200% increase in embodied energy coefficient in comparison to glasswool[1]	Greece	EPS has a 180% increase in energy coefficient compared to glasswool	
	Can lower the OE by 20% in comparison to glasswool[2]	Sweden	Lowered OE by 3%	Lowered OE by 4%
Straw	Lower IEGHGE and decreases OGHGE[3]	Australia	Decrease between 2% and 6% in IEGHGE for R2 Straw compared to R2 glasswool	Decrease between 4% and 7% in IEGHGE for R2 Straw compared to R2 glasswool
	Can decrease space heating by 20%[4]	Egypt	Between 6 and 10% decrease in OGHGE	Between 3 and 8% decrease in OGHGE
	Benefits of straw bale are less in hot/ humid climates than for colder climates[5,6]	USA		
R-Value increase	Increase in R-Value results in an increase in IEE[7]	Belgium	Between 6% and 14% increase in IEGHGE when increasing R2 to R3	Between 5% and 11% increase in IEGHGE when increasing R2 to R3
	Potential to decrease OE and can be between 22% to 79%[8]	Turkey	Between 9% and 18% decrease in OGHGE when upgrading from R2 to R3	Between 7% and 12% decrease in OGHGE when upgrading from R2 to R3
	7% decrease in OGHGE when changing from R2 to R3[9]	Sydney		
	Higher ceiling R-value for hotter climates more beneficial than for	USA	R5 and R6 ceiling insulation upgrade results in between	R5 and R6 ceiling insulation upgrade results in between 4% and 6%

Insulation type	Comparison to other study and location	This study: Melbourne results	This study: Gold Coast results
	colder climates[10]	0.4% and 1% decrease in OGHGE	decrease in OGHGE

Sources: [1] *Anastaselos et al. (2009),* [2] *Tettey et al. (2014),* [3] *Downton (2013),* [4] *Garas et al., (2009),* [5] *Geiger (2001),* [6] *Morrison (2007) ,*[7] *Stephan et al. (2013),* [8] *Bolatturk (2006),* [9] *Bambrook et al. (2011),* [10] *Inerney (2011)*

5.4.1.2. Life cycle cost results

A summary of the framework's LCC results and other previous similar studies is provided in Table 5.10. Several studies, including Hasan (1999) and Ozel (2012), also found that the initial cost of insulation increases as insulation thickness (and thus R-Value) increases, as is evident from the results above (see Section 5.3.1) when increasing wall insulation from the Base Case R2 up to R3 and the same when increasing the ceiling insulation from the Base Case's R4 to R6. The same study confirms that as insulation increases the operational costs of a building decrease, similar to the Base Case operational cost decrease when using R3 instead of R2 wall insulation. For their study of a Sydney house, Bambrook et al. (2011) also found an improved LCC performance between R2 wall insulation and R3 (even with the increased initial cost), similar to the findings of this study. Ozel (2012) also found that glasswool insulation provided greater financial savings when compared to EPS regardless of what thickness was applied to the building. Similar to this study, (Leusch, 2011) also found an initial cost increase of roughly 50% (which in turn increased the LCC) for straw insulation due to the labour intensive construction techniques associated with this type of insulation.

Ozel (2012), and others such as Dombayci and Pancar (2006), explored the existence of a certain optimal point where increasing the insulation level further will result in a minimal increase in total financial savings. For Ozel's example it was found that the energy savings for glasswool increase only marginally from 100mm to 160mm. However, it should be noted that this study took place in Turkey, which is classified as a Mediterranean climate and will present different results when compared to a Melbourne-based building. Aspects that have been demonstrated to influence the life cycle cost results of insulation significantly include the extent of insulation application, orientation of the building, surface colour, location and type of materials (Yu et al., 2009).

However, it is important to bear in mind that the comparison of LCC results across different studies is quite a controversial exercise as the results depend on a multitude of inputs and the assessor's assumptions, from DR, MSL, IR etc.. The high level of uncertainty regarding life cycle costing, of which a significant proportion of this uncertainty lies within the input values selected (Babashamsi et al., 2016; Gluch and Baumann, 2004), must be taken into account when interpreting and validating these results. The LCC method as a whole has been deemed unreliable in studies such as Cole and Sterner (2000) due to the high level of uncertainty. However, as there is no other (more reliable) option available at present, LCC, using the NPV approach, has been deemed reliable enough to indicate the potential for showing the economic trade offs of strategies against their environmental aspects for this study's framework.

Table 5.10 Comparison to previous studies for insulation LCC

Insulation type	Comparison to other study and location		This study: Melbourne results	This study: Gold Coast results
EPS	Glasswool provided greater financial savings in comparison to glasswool[1]	Turkey	Roughly 5% LCC decrease when comparing EPS to glasswool	Roughly 4% LCC decrease when comparing EPS to glasswool
Straw	Higher initial cost due to the fact that it requires labour intensive construction techniques[4] which can cost 50% more than a conventional house[3]	Australia	Increase of roughly a 60% in initial cost when compared to R2 glasswool wall insulation	Increase of roughly a 50% in initial cost when compared to R2 glasswool wall insulation
R-Value increase in glasswool	Initial cost increase when increasing insulation thickness and R Value[1,2]	Turkey	Roughly 30% initial cost increase from R2 to R3 wall insulation	Roughly 22% initial cost increase from R2 to R3 wall insulation
	Insulation increase can decrease the operational cost	Turkey	Roughly 6% operational cost decrease when changing from R2	Roughly 5.5% operational cost decrease when changing from

Insulation type	Comparison to other study and location		This study: Melbourne results	This study: Gold Coast results
	of the building[1,2]		to R3 wall insulation	R2 to R3 wall insulation
	LCC decrease when upgrading from R2 to R3 wall insulation[5]	Australia	Roughly 5% LCC decrease when changing from R2 to R3 wall insulation	Roughly 4% LCC decrease when changing from R2 to R3 wall insulation

Sources: [1] *Ozel (2012),* [2] *Hasan (1999),* [3] *Leusch (2011),* [4] *Downton (2013),* [5] *Bambrook et al. (2011)*

5.4.2. Comparison of glazing results to previous studies

5.4.2.1. Life cycle greenhouse gas emissions results

A summary of framework's LCGHGE results and other previous studies are provided in Table 5.11. Similar to this study, Howard et al. (2007) found that for a mild climate such as Melbourne, the difference between SG and DG, in terms of operational energy and OGHGE reduction, is marginal. Aldawi et al. (2013) found a 14% reduction in total annual operational energy for their Melbourne-based dwelling when changing SG to DG. Lawania and Biswas (2016) found for their Perth-based study (Perth can be classified as warm and temperate (Climate-Data.org, 2016)) that only an 8% OGHGE reduction occurred in a brick veneer house when replacing SG with DG.

Jones (2014), in his London-based study (a temperate climate similar to Melbourne) found a decrease of roughly 10% in operational GHGE when switching from DG to TG windows (both timber and aluminium yielded the same results). Jaber and Ajib, (2011) concluded that TG was best for most climate regions (from Berlin to Amman) but is not economically feasible. Bosschaert (2009) in his Rotterdam-based study (also a temperate climatic location) found a steady decrease in energy use when switching from SG to DG to TG, however the amount of decrease was not drastic from SG to DG. Menzies and Wherret (2005) found only a 5% reduction in energy use when changing from AF to TF, which is slightly higher than the 4.5% found in this analysis. Switching to DG and even TG can result in an increase in initial and recurrent embodied GHGE, however the exact value is not specified (Menzies and Wherret, 2005). Asif et al. (2011) also found that aluminium windows account for the highest IEE when compared to timber or PVC windows. Asif et al. (2011) found an 80% reduction in IEE when switching from aluminium to timber-framed windows. A study completed by Recio et al. (2005) found a 96% reduction in IEE when switching from AF to TF. Similar to this analysis, Jones (2014) found a 53% reduction in IEE when switching from aluminium to timber windows.

Howard et al. (2007) concluded that in Australia it is not universally true that high performance windows will recover their extra embodied impacts over the life because most populated areas of Australia have mild climates with low heating and cooling loads. However, as Jones (2014) concluded, when faced with glazing decisions, the frame type is more important than the choice of double or triple glazing when considering the building's performance from a life cycle perspective. This is similar to the findings of this analysis as the frame's MSL and frame embodied energy coefficient had a significant influence on the LCGHGE results, with timber windows being favoured over aluminium windows for lowering GHGE. It is also important to take the solar heat gain coefficient (SHGC) into account (as it can influence the behaviour of the glazed unit), for colder climates a high SHHC is better and for warmer climates a lower SHGC is better (AGGA, 2017; Schnieders et al., 2015). Heating load is also very sensitive to glazing extent. Both these aspects will have to be researched in greater detail in future studies.

Table 5.11 Comparison to previous studies for glazing LCGHGE

Glazing type	Comparison to other study and location		This study: Melbourne results	This study: Gold Coast results
Double glazing	14% reduction in operational energy when switching from SG to DG[1]	Melbourne	25% reduction in OGHGE when switching from SG_AF to DG_AF	20% reduction in OGHGE when switching from SG_AF to DG_AF
	8% reduction in operational energy when switching from SG to DG[2]	Perth		
	Increase in IEGHGE when switching from SG to DG[4]	Edinburgh	5% increase in IEGHGE when switching from SG to DG	4% increase in IEGHGE when switching from SG to DG
Triple glazing	10% reduction in operational energy when switching from DG to TG[3]	London	5% reduction in OGHGE when switching from DG_AF to TG_AF	4% reduction in OGHGE when switching from DG_AF to TG_AF

Glazing type	Comparison to other study and location		This study: Melbourne results	This study: Gold Coast results
	Increase in IEGHGE when switching from SG to TG[4]	Edinburgh	7% increase in IEGHGE when switching from DG to TG	6% increase in IEGHGE when switching from DG to TG
Frame material	Both timber and aluminium framed windows provided very similar results[3]	London	4.5% reduction in OGHGE when switching from AF to TF	3% reduction in OGHGE when switching from AF to TF
	5% reduction in operational energy when switching from AF to TF[4]	Edinburgh		
	80% reduction in IEE when switching from AF to TF[5]	UK	53% reduction in IEGHGE switching from AF to TF	55% reduction in IEGHGE switching from AF to TF
	96% reduction in IEE when switching from AF to TF[6]	Spain		

Sources: [1] *Aldawi et al. (2013),* [2] *Lawania and Biswas (2016),* [3] *Jones (2014),* [4] *Menzies and Wherret (2005),* [5] *Asif et al. (2011),* [6] *Recio et al. (2005)*

5.4.2.2. Life cycle cost results

A summary of the framework's LCC results and other previous studies are provided in Table 5.12. Most previous studies have found that TG typically has the highest initial cost (Bosschaert, 2009; Jones, 2014) and DG to cost more than SG regardless of the frame type used (Bambrook et al., 2011). Bosschaert (2009), with a 3% IR similar to this analysis, also found significant financial savings in terms of energy costs, when switching from DG to TG (however the DR is not provided and the costs are presented in Euros, not AUD). This study stated that TG, in comparison to DG, will repay its extra 11 kg CO_2e per year in a matter of months. However, though this framework's demonstration found a similar increase in GHGE (approximately 13 kgCO_2e per year extra when comparing DG to TG), it does not result in a net GHGE reduction due to the high IEGHGE and REGHGE of triple glazed units. It is assumed that Bosschaert's study probably used the more common process data, which excludes multiple upstream life cycle influences, and several other inputs are unclear such as DR and MSL, which could have influenced their LCC results.

A Jordanian study, by Jaber and Ajib (2011), also found a decrease in LCC of between 2% and 4% when switching from SG to DG (similar to the findings of this study of 1% for AF and 3% for TF). However, the IR used of 8.9% is significantly higher than the framework's demonstration of 3%, which could influence the findings. An Australasian study that used a DR slightly higher than the current study of 6.5%, also found that the LCC increases when comparing DG with SG, due to the operational and replacement energy savings (Mithraratne et al., 2007).

It is important to bear in mind that the comparison of LCC results across different studies is quite a contentious exercise as the results are so dependent on a multitude of inputs and the assessor's assumptions, such as DR, MSL, IR etc.

Table 5.12 Comparison to previous studies for glazing LCC

<table>
<tr><th>Glazing type</th><th colspan="2">Comparison to other study and location</th><th>This study: Melbourne results</th><th>This study: Gold Coast results</th></tr>
<tr><td rowspan="3">Double glazing</td><td>Reduction in operational energy when switching from SG to DG (with IR 3%)[1]</td><td>Rotterdam</td><td colspan="2">Over 200% decrease in operational cost when switching from SG to DG</td></tr>
<tr><td>LCC decrease of between 2% and 4% when switching from SG to DG (with IR 8.9%)[2]</td><td>Jordan</td><td colspan="2" rowspan="2">Decrease of ±5% found when switching from SG_AF to DG_TF. However, increase in LCC of ±8% when switching from SG_AF to DG_AF (due to higher initial cost)</td></tr>
<tr><td>LCC increase when switching from SG to DG (DR of 6.5%)[4]</td><td>Australasian</td></tr>
<tr><td>Triple glazing</td><td>Highest initial cost in comparison to SG and DG (IR and DR unknown) [3]</td><td>London</td><td colspan="2">TG_AF has almost 200% increase in initial cost when compared to SG_AF</td></tr>
</table>

Sources: [1] *Bosschaert (2009), 2 Jaber and Ajib (2011),* [3] *Jones (2014),* [4] *Mithraratne et al. (2007)*

5.5. Summary

This chapter applied the environmental and economic integrated framework to a built environment example. This application provided an example of the results the framework can achieve, examples of the graphical outputs that can be used and an example of how the framework can guide the decision-making process. This chapter also demonstrated how the aim of the framework was achieved, which was to integrate environmental and economic building performance in order to demonstrate the relationship and trade-offs between these two factors. This demonstration was achieved by applying the integrated framework to various aspects, as summarised in the diagram in Figure 5.18. This included using a residential case study building, located in Melbourne and Gold Coast, and two different building elements, insulation and glazing. The integrated framework approach, consisting of Step 1 to Step 9, was applied to each scenario, as illustrated in Figure 5.18.

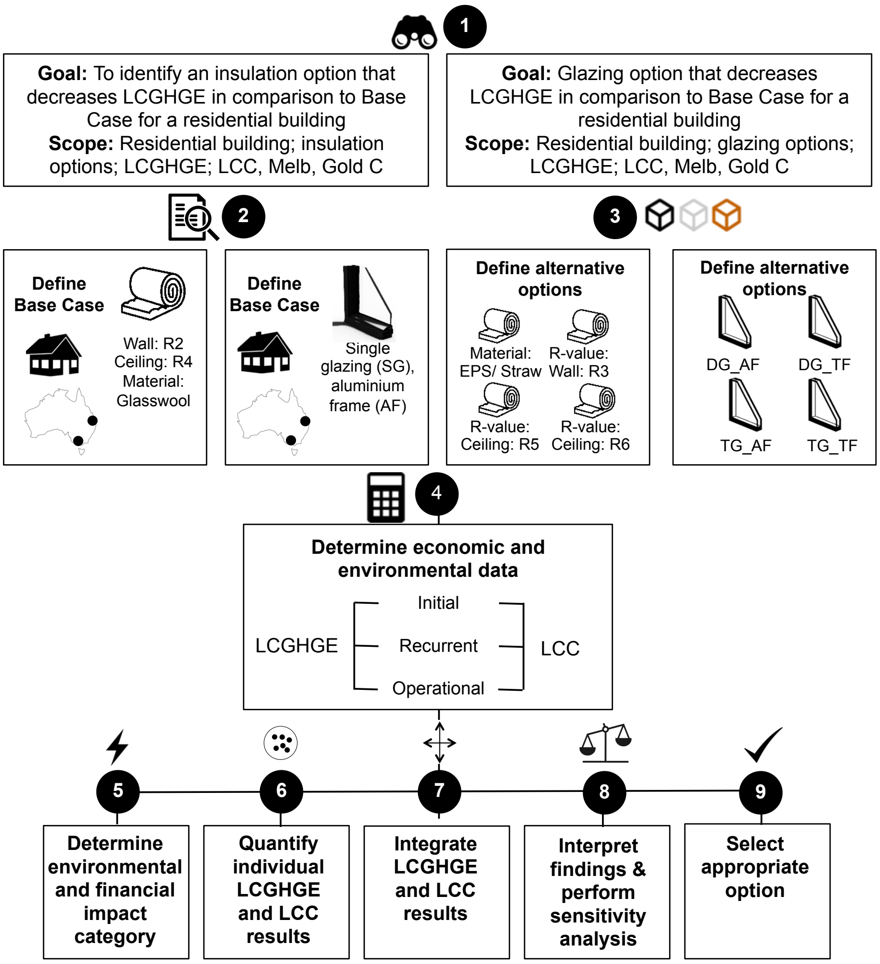


Figure 5.18 Summary of the aspects included in the demonstration of the integrated framework

Table 5.13 provides a brief summary of the aspects tested in this chapter and the results achieved.

Table 5.13 Summary of key results of the framework demonstration for the residential case study building for the insulation and glazing scenarios

Building element	**Summary of results: Melbourne**	**Summary of results: Gold Coast**
	• Straw insulation consistently provides a reduction in LCGHGE regardless of the sensitivity parameter selected, however comes at a potential increased LCC. • R3 wall insulation provides both a reduction in LCGHGE and LCC.	• Straw, R3 wall insulation along with R5 and R6 ceiling insulation decreases the LCGHGE when compared to the Base Case. R6 ceiling insulation provided the greatest LCC and LCGHGE reduction. Straw insulation resulted in an increase in LCC.
	• All glazing options lead to a decrease in LCGHGE when compared to the Base Case however result mostly in an increased LCC. • TG_TF consistently provides a LCGHGE reduction regardless of sensitivity parameter selected however has a possible increased LCC. • Only DG_TF provides a decrease in LCC for every tonne of CO_2e reduced.	• All glazing options lead to a decrease in LCGHGE when compared to the base case. TG_TF provided the greatest LCGHGE decrease (however not as much as for the Melbourne case study location). • Only DG_TF provided both a decrease in LCGHGE and LCC when compared against the Base Case.

Through the results generated in this chapter the following key items were successfully demonstrated:

- How the developed framework addressed one of the main gaps of previous studies in the fact that it was actually applied to a built environment example.
- The flexibility, adaptability and capability of the framework in the fact that it can help analyse different design options in different locations.
- An example of the results that can be achieved by using the integrated framework. From the detailed individual LCGHGE and LCC results breakdown per life cycle stage to the integrated LCGHGE and LCC results.

Results were also presented in a range of possible graphic options from bar and column charts to scatter plots.

- The importance of assessing GHGE and cost from a whole life cycle perspective. For example, if the glazing scenarios for Melbourne were only assessed from an initial cost perspective, SG_TF would have been selected, which resulted in an increase in LCC, whereas DG_TF resulted in a decrease in LCC, regardless of the increase in initial cost.
- The results achieved by the framework are comparable with previous studies.
- A comprehensive means to analysing LCGHGE and LCC through the Path Exchange hybrid approach (which include multiple upstream impacts usually neglected in embodied GHGE analysis) and NPV (which took time value of money into account).
- How integrated LCGHGE and LCC results can inform and alter the decision-making process compared to considering only one (either just LCGHGE/LCC). For example, if a decision was purely based on reducing LCGHGE for the Melbourne residential glazing analysis, any of the glazing options could be selected, with TG_TF providing the greatest reduction. If an option was selected from a purely LCC reduction point of view, DG_TF would be selected. However, from an integrated LCGHGE and LCC perspective, DG_TF would appear to be the most ideal.
- The importance of the sensitivity analyses step (Step 8). Parameters like POA have a significant influence on the LCGHGE reduction potential and DR on the LCC result. It demonstrated how this step can further inform decision-making as, for example, the user can be more assured of the LCGHGE reduction potential of straw insulation (as the results were consistently placed in Q4 and Q3), or of R3 wall insulation's LCC reduction potential (with results consistently in Q3 and Q2) through the sensitivity analysis.
- It also demonstrated how the gaps in previous studies were addressed (as outlined in Chapter 4, Table 4.1). All relevant inputs and calculations are provided, all relevant life cycle stages are included, data is based on information typically available at an early stage design, the framework is applicable to building scale analysis and the final selection of design option is informed by the user's personal preferences.

Several of the aspects described above form the basis of the following Discussion chapter, including reference to their significance to the future development of the integrated framework.

6.

Discussion

6.1. Introduction

The aim of this study was the development of a framework for the integrated optimisation of the environmental and economic performance of buildings. At present, environmental and economic building performance are predominantly analysed in isolation of each other. This weakness has been successfully addressed in this study by the combination of these two complimentary building assessments in a meaningful and comprehensive manner through the means of a decision-support framework. This framework provides a more detailed understanding of the relationship and trade offs between these two factors for better informed building design decisions and also supports the creation of an environmentally sound built environment.

Chapter 2 emphasised the need to evaluate building designs from both an environmental and economic perspectives. The vital importance of basing building related decisions on a life cycle perspective was also discussed. Initial cost is often the main determinant in financially related decisions, and operational energy or GHGE in environmental decisions, often ignoring the other life cycle stages. There is also great uncertainty regarding the financial implications of life cycle environmental optimisation. Several studies have attempted to provide an integrated environmental and economic assessment, but several weaknesses and gaps still have to be addressed in order to further optimise this integration process (as discussed in Section 3.2.2).

The major significant contribution of this study is the successfully developed environmental and economic framework which comprises the following: the approach, (as outlined in Section 4.2.3), a detailed list of the pre-defined input parameters (as outlined in Section 4.2.4), examples of user defined inputs (as outlined in Section 5.4.5, 5.5.5, 5.6.5, and 5.7.5), visual output options (as outlined in Section 3.2.9) and a detailed list of sensitivity parameters (as outlined in Section 3.2.10). The developed framework made use of the following decision support tools, LCA for the environmental assessment, LCC for the economic assessment (as outlined in Section 3.3.1) and MCDM for the integration of environmental and economic criteria (as outlined in Section 3.3.2).

The developed framework contributes to the rapidly evolving field of LCA and LCC integration (such as Schwartz et al. (2016), Ristimäki et al. (2013), Petrillo et al. (2016), and Leckner and Zmeureanu (2011)) but addresses the current gaps of this field (as outlined in Section 3.2.2 and Section 4.2.1). In addition, this study contributes to the growing body of research on the more comprehensive Path Exchange hybrid approach for its embodied GHGE quantification, which includes studies such as Crawford (2008), Stephan and Stephan (2016), Rauf and Crawford (2013) and Treloar et al. (1999). Another significant contribution of this study is the demonstration of the relationship and trade-offs between environmental and economic optimisation, as explored in Chapter 5, by applying the framework to a case study building.

The purpose of this chapter is to discuss the implications of the results presented in Chapter 5. These results were based on the research design presented in Chapter 3, which formed the basis of the development of the framework in Chapter 4, which in turn was an interpretation of the background literature presented in Chapter 2.

The chapter includes a description of this study's major findings, which have been divided into three main categories:

- Environmental and economic framework development
- Residential case study building findings
- Addressing uncertainties in life cycle studies results

This is then followed by a discussion of the implications of this research's findings for the discipline and industry, and concludes with a discussion of the limitations of this study.

6.2. Environmental and economic framework development

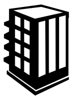
This section has been divided into five parts. The first part provides a brief overview of addressing the gaps of previous studies in the developed framework, followed by the provision of a roadmap for future environmental and economic framework development. The third part provides a discussion of how the framework entails a more comprehensive approach for assessing the environmental and economic performance of buildings. This is followed by setting out how the framework guides the decision-making process and included user personal preferences. This section concludes with an overview of the adaptability, capability and reliability of the framework.

6.2.1. Addressing the gaps of previous studies

The developed framework addresses the gaps and weaknesses identified in previous studies (set out in Section 3.2.2 and Table 3.1). Table 6.1 summarises the gaps and provides further detail as to how this study's framework has addressed them.

Table 6.1 Gaps in previous studies and how this study's framework has addressed them

Gaps in previous studies	How this study's framework has addressed them
Lack of transparent inputs/ calculations	All calculations (Refer to Section 3.2.6.1 to 3.2.7, and equations 3.1 to 3.15) all variables included in the calculations have been provided along with the relevant sources. Refer to Appendix B for pre-defined inputs and Appendix C for user-defined inputs. Additional economic and environmental data are provided in Table 5.4 and Table 5.5.
Incompleteness in embodied GHGE calculations	The more comprehensive Path Exchange Hybrid approach was used to quantify embodied GHGE. This approach includes more upstream impacts compared less comprehensive methods such as Process analysis. Refer to Section 3.2.6.1 to 3.2.6.3 for more detail and Table B5 in Appendix B for example of embodied energy coefficients. Refer to equations 3.1 to 3.7 for Path Exchange Hybrid calculations.
Lack of visually integrated environmental and economic results	All outputs have been provided in a visual format. Results have been provided in bar and column charts. Refer to Figures 5.5 and Figures 5.6 for examples of column charts for LCGHGE and LCC breakdown per life cycle stage. Refer to Figure 5.8 for an example of a bar chart for LCC/tCO_2e reduced. Integrated results have been visualised with the help of a scatter plot (Refer to Figure 5.7 for an example of a scatter plot that integrates LCGHGE and LCC results for insulation scenarios). Sensitivity analysis results have also been visualised with the help of a shaded scatter plot (Refer to Figure 5.9).
Lack of weighting/ scaling factor explanations	All results have been provided in a transparent manner (i.e. LCGHGE results have been provided in tCO_2e and LCC results have been provided in AUD). No weighting or scaling have been applied to the framework results (therefore no further explanation required) but can be applied for future use. Refer to results in Section 5.3.1.7 and 5.3.2.7.
Lack of recurrent embodied GHGE and	Recurrent embodied GHGE and replacement cost have been included in the framework. Refer to Section 5.3.1.6 and Section 5.3.2.6.

Gaps in previous studies		How this study's framework has addressed them
	replacement cost inclusion	
	Lack of operational GHGE and operational cost inclusion	Operational GHGE and operational cost have been included in the framework. Refer to Section 5.3.1.6 and Section 5.3.2.6.
	Lack of building scale analysis	The framework has been applied to a case study building, namely a residential detached building, in Chapter 5. Refer to Section 5.2.1 for a description of the case study building.
	Lack of early stage design application	Information used within this study's frameworks is based on data typically available at an early stage in the design, to increase the potential for influencing the design earlier. Refer to Table 5.4 and Table 5.5.
	Lack of selection process based on user personal preferences	The framework results have been presented in a manner that allows users to base their interpretation and selection of building options on their own personal preferences (for example either select an option, that decreases LCGHGE the most with no consideration to financial cost, or select an option that decreases LCGHGE and LCC). Refer to Section 5.3.1.9 and Section 5.2.2.9.

The integration of environmental and economic building analysis, particularly in the form of LCA and LCC, is a rapidly evolving field of study. This study's framework is the first integrated environmental and economic framework known to address all the gaps listed above. One of the most critical factors of previous studies is that their embodied energy and GHGE calculations are based on the less comprehensive approach of process analysis (Gu et al., 2008; Schwartz et al., 2016; Savino et al., 2017). Process analyses, as discussed earlier in Chapter 2, have shown to ignore multiple upstream impacts. This study goes beyond that and uses the more comprehensive Path Exchange Hybrid approach (as is evident from Sections 3.2.6.1 to 3.2.6.3) and joins the very limited number of LCA and LCC studies that use this approach, such as Stephan and Stephan (2016).

Another aspect that sets the developed framework apart from most integrated environmental and economic studies is that it not only applied the framework to a built environment example (refer to Chapter 5) but also provides the results of this integration in a visual format (refer to Figures 5.7, 5.9 and 5.14 for example), unlike Anastaselos et al. (2009), Hoogmartens et al. (2014) and Petrillo et al. (2016). The application of the framework is vital in order to demonstrate its potential and to inform users how to use it in a practical manner. Most previous studies remained at a theoretical level without applying it to a practical built environment example, in contrast with this study. Providing results in a visual format is also essential to facilitate the user's interpretation of results, as it has been demonstrated that most people struggle with the interpretation of numbers and the use of a graph can better demonstrate the relationship between variables (Baez et al., 2012). These visually integrated results joins the limited number of studies that have also provided this, such as Stephan and Stephan (2017) (however, their study was based on a life cycle water perspective and not LCGHGE), Ristimäki et al. (2013) (however, their study uses input-output analysis for their embodied energy and GHGE calculations which suffers from truncation error, and only applied their framework to exemplar technologies, such as district heating, not to traditional buildings and technologies which make up the majority of the built stock) and Schwartz et al. (2016) (their study also made use of process analysis).

Most previous studies developed new tools or methods to integrate environmental and economic performance, such as Gu et al. (2008) and Anastaselos et al. (2011). However, as Kovacic and Zoller (2015) stated, the problem with life cycle studies is not the need to create more tools and more methods but rather to harness what has already been established. This study uses a framework, which provided an ideal basis for harnessing the methods already used within environmental assessment, namely LCA, and economic assessment, namely LCC, and draws upon their strengths. By using the existing frameworks (such as those for LCA in ISO 144044 and LCC in ISO 15686), existing quantification techniques and existing data, this study's framework helps to evolve the practice of life cycle assessment instead of attempting to redefine it. This study's framework contributes to the limited number of earlier environmental and economic frameworks, such as Deng et al. (2008) and Heijungs et al. (2013). However, the developed framework goes beyond these two previous studies as it was applied to an actual built environment example (of which their studies did not), uses Path Exchange Hybrid approach for embodied energy and GHGE quantification (their studies made use of process analysis) and provides a visually integrated format of results (a major shortfall of these two previous studies).

6.2.2. Providing a roadmap for environmental and economic framework development

This study developed an approach for the integration of environmental and economic building analysis into a single comprehensive framework. This was achieved through the creation of a step-by-step process (see Section 3.2. and Section 3.4) and the integration of decision-support frameworks such as LCA, LCC and MCDM (see Sections 3.2.3 to 3.25). This study also used existing LCA and LCC quantification techniques (see Section 3.2.6) and defined the associated input parameters (see Section 4.2.4). The developed framework further incorporated sensitivity analysis and defined the specific sensitivity parameters that must be considered (see Section 3.2.10 and 5.3.1.8 and 5.3.2.8) and also enabled the visualisation of outputs (see Section 3.2.9 and Figures 5.5 to 5.17).

The framework provides a roadmap that can be used by future researchers to improve design decision-making and provides methods for concurrent optimisation of environmental and economic building performance evaluation, as illustrated in Figure 6.1.

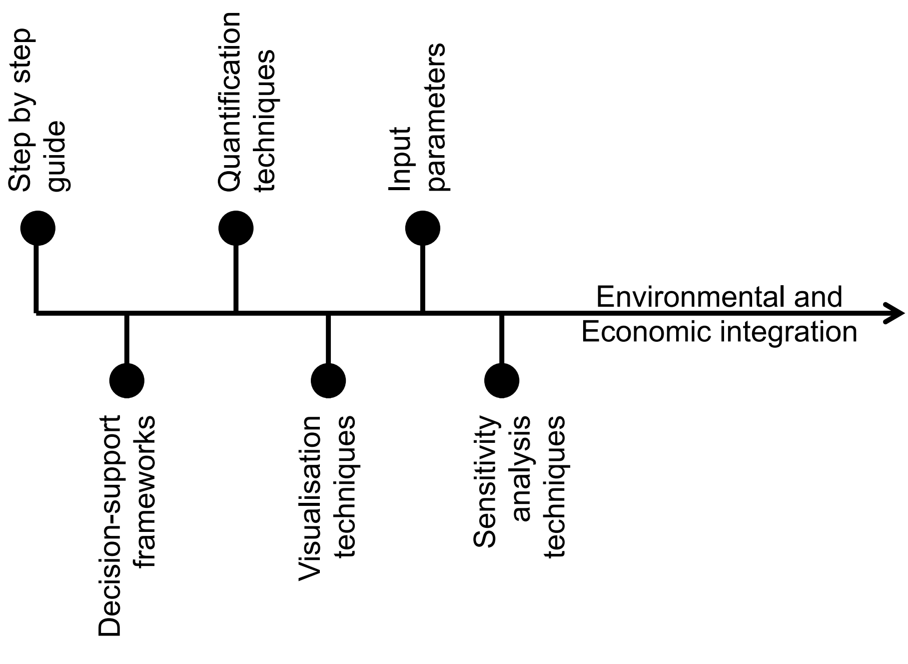


Figure 6.1 Integrated environmental and economic building performance analysis roadmap

6.2.3. Towards a more comprehensive approach for assessing environmental and economic building performance

The developed framework provides a for more comprehensive approach for the integration of environmental and economic building performance analysis, in comparison to previous studies, through the use of the following: the Path Exchange hybrid method for embodied GHGE quantification, the NPV approach for LCC quantification, and One-At-a-Time (OAT) approach for sensitivity analysis.

Most previous studies use process analysis (for example as Bovea and Vidal (2004), Bull et al. (2014) and Savino et al. (2017)). This form of analysis fails to account for multiple upstream impacts and has been demonstrated to underestimate the embodied impact of a building by more than 80% (Crawford, 2008). By using the Path Exchange hybrid method within the framework, the most comprehensive analysis of embodied GHGE becomes possible. Refer to Section 2.3.3 for an overview of this approach, Section 3.2.6 for quantification techniques associated with this approach and Section 5.3.1.6 for an example of the results that can be achieved using this approach.

The framework makes use of the NPV approach for the quantification of LCC. It has been demonstrated to be one of the more reliable tools for economic analysis (Berk and De Marzo, 2014) as takes into account the time value of money. Its relevance to integrated environmental and economic studies, particularly from a LCA and LCC perspective, has also been demonstrated by its use in similar previous studies, for example Ristimäki et al. (2013) and Kneifel (2010). However, unlike this study, neither of these studies provide the actual calculations used and consequently it is not clear what variables were included in their analysis. Refer to Section 2.4.2 for more detail about the NPV approach, Section 3.2.7 for the relevant calculation and Section 5.3.1.6 for an example of the type of results that can be generated by its use.

A vital component of the framework was the inclusion of a sensitivity analysis (Step 8 as per Section 4.2.3). Life cycle studies suffer from a significant amount of uncertainty, as the assessor has to predict the future and include several assumptions about this prediction. The various methods available for sensitivity analysis were discussed in Section 3.2.10 and a summary provided in Table 3.8. For the framework's demonstration in Chapter 5, the OAT approach was selected, as it is easy to perform and appropriate to the amount of data available at an early stage of building design. An example of the results of this sensitivity analysis was provided in Section 5.3.1.8 and 5.3.2.8 and formed an integral part of the development of the framework (as discussed in Section 6.4 below). Most earlier studies do not provide a sensitivity analysis for their integrated environmental and economic results, such as Langston and Langston (2008) and Deng et al. (2008). This study is one of a small number of integrated environmental and economic studies that include a sensitivity analysis, such as Stephan and Stephan (2017).

6.2.3.1. Guiding the decision-making process and inclusion of user preferences

The developed framework takes the user's personal preferences into account, which allows for much greater flexibility. It is important to note that no single 'optimal' solution for all users exists, as each user will have individual expectations, preferences and needs, which is an integral part of any MCDM process (Ho, 2008). The framework's final basis of design selection is entirely dependant on the goal of the study (for example, whether the goal was to select an insulation option that leads to the greatest decrease in LCGHGE without any cost concern, or whether both a LCGHGE and LCC reduction was required).

An example of how the decision-making process can be guided by this flexibility is provided in Figure 6.2 and Figure 6.3, which demonstrates which insulation scenario for the Melbourne and Gold Coast residential case study building (see Section 5.2.3), may be selected, based on different perspectives and goals (such as only LCGHGE reduction or only LCC reduction or both LCGHGE and LCC reduction). For example, when the framework was applied to the same case study building, for both locations insulation analysis a user wanting to select a strategy based only on the LCGHGE performance, may select any strategy other than EPS (refer to Figure 6.2 and Figure 6.3). But for a Gold Coast users wanting to base their decision on both a LCGHGE and LCC reduction perspective, may select R6 ceiling insulation (refer to Figure 6.3) for this specific case study (see Section 5.2.1), unlike a Melbourne user who would select R3 wall insulation (refer to Figure 6.2).

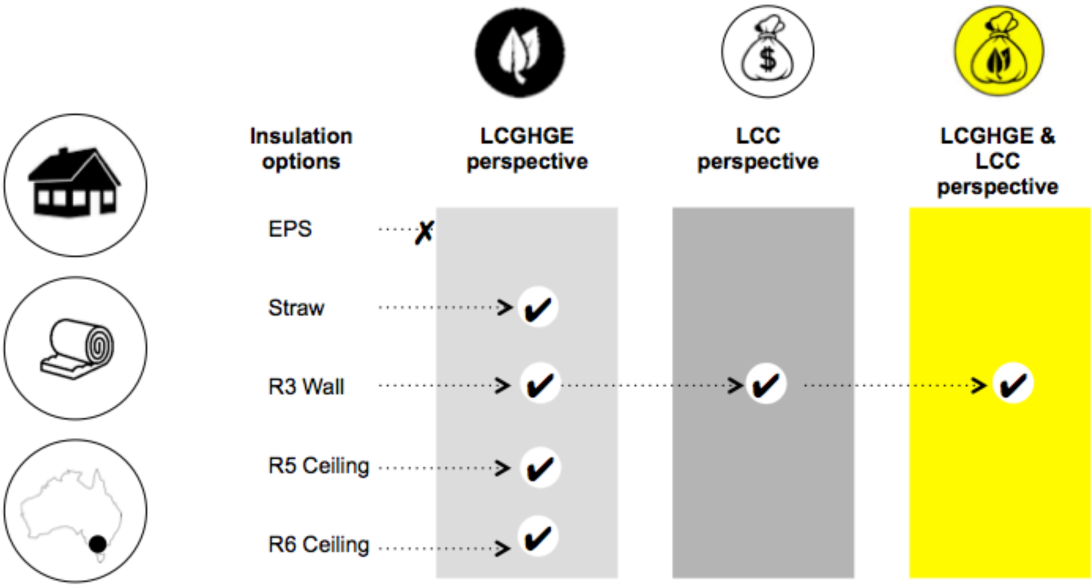


Figure 6.2 Guiding the decision-making process for the residential insulation analysis for Melbourne based on the user's personal preferences

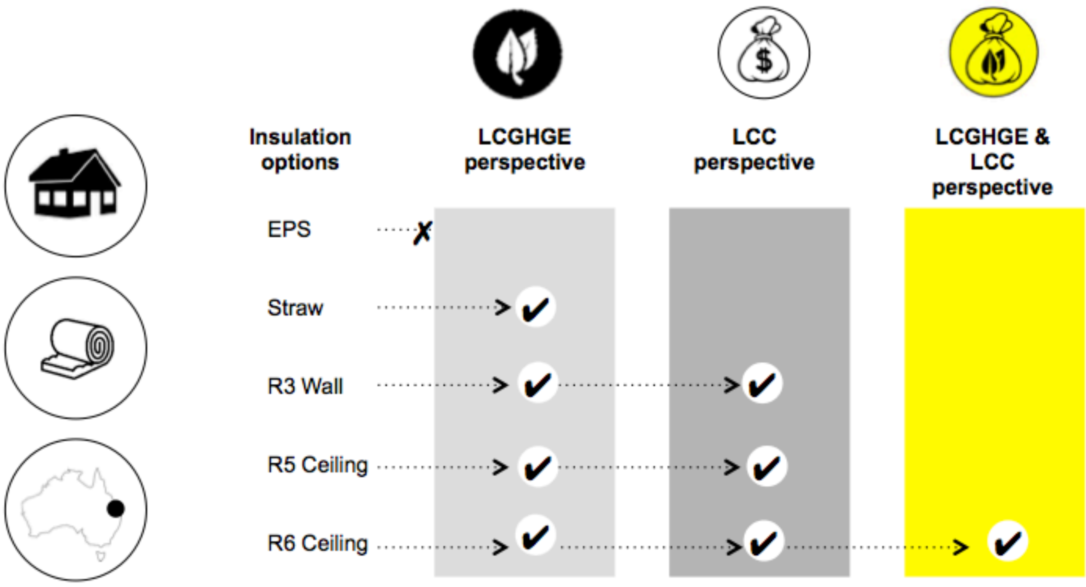


Figure 6.3 Guiding the decision-making process for the residential insulation analysis for Gold Coast based on the user's personal preferences

The developed framework's greater flexibility in terms of user's personal preferences helps to address one of the gaps from previous studies. Several previous studies, such as Deng et al. (2008) and Savino et al. (2017), provide the final results based on terms like 'integrated benefit' or 'intolerable'. However, what might be 'intolerable' to one user may be 'tolerable' to another. It is vital for the final selection to be based on the user's own personal preferences, which is possible within the framework developed in this study.

6.2.4. Adaptability, capability and reliability of the framework

The framework adaptability was demonstrated by applying it to two different building elements, being insulation and glazing. The framework approach was adapted for each form of analysis (refer to Figure 5.3 and 5.10) and applied to demonstrate the outputs of the framework for a range of insulation and glazing scenarios (refer to Section 5.3.1and 5.3.2). The adaptability of the framework was further demonstrated by its capability to also analyse a case study building in two different locations (see Section 5.2.3), namely Melbourne and Gold Coast. Most previous studies only considered one location, for example Bovea and Vidal (2004) (Spain), and Gu et al. (2008) (Beijing), or only one building element, for example Savino et al. (2017) (who looked only at wind turbines). The inclusion of two different building elements and two different locations were essential for demonstrating that the framework can be applied across a wide range of possible building related scenarios. While this study covered more scenarios than previous studies, an even greater number of scenarios will be essential for the understanding of the broader applicability of the framework. Additional building materials, elements and typologies should be analysed, but falls outside the scope of this study.

The reliability of the developed framework was demonstrated in Section 4.2.5, where the application of the framework's quantification techniques were validated through favourable comparison to previous similar studies, and in Section 5.4, where the insulation and glazing LCGHGE and LCC results were compared to similar studies (as summarised in Table 5.9, 5.10, 5.11 and 5.12).

The ability of the developed framework to adapt to different building design decisions, to assess different locations and provide comparable and reliable results demonstrates its robustness, flexibility and adaptability.

6.3. Residential case study building findings

The application of the framework to a residential case study building (Chapter 5) provided an example of the environmental and economic trade-offs of the assessment of various design solutions. This section discusses the major findings associated with this specific case study, and the implications for the development and use of the framework.. The first part of this section provides an overview of the case study's results in terms of the relationship and trade-offs between environmental and economic building performance. The next part describes the affordability of GHGE reduction design options for the case study. This section then concludes with an overview of the importance of contextual characteristics and the life cycle perspective.

6.3.1. Relationship and trade-offs between environmental and economic building performance

The framework created in this study provided a successful example of how the examination of the trade-offs between environmental and economic factors in building performance evaluation. For example, in Section 5.3.1.8, R3 wall insulation was seen to decrease LCC regardless of the sensitivity parameter selected, but leads to a possible increase in LCGHGE. In comparison, straw insulation, which consistently decreased the LCGHGE, results in a potential increase in LCC. Similar trade-offs can be seen in the glazing results (refer to Figure 5.16) where options like triple glazing with a timber framed windows have the potential to elevate LCC but with increased prospects of resulting in the greatest LCGHGE reduction, regardless of the sensitivity parameter is selected. These results demonstrated how the developed framework could be used successfully to examine trade offs, and that the sensitivity analysis can form a vital part of the main assessment.

This study has also demonstrated that known factors that contribute to an improved GHGE performance, for instance selecting more robust materials with longer MSL and advocating longer building service life (BSL) (Crawford, 2011; Sturgis and Roberts, 2010), also have a beneficial impact on the LCC performance of a building. For example, this is evident in the glazing results (Section 5.3.2.7), where timber-framed windows, which generally have a longer MSL than aluminium windows (Rauf and Crawford, 2013), lead to lower LCGHGE and LCC. Triple-glazed timber-framed windows decrease the LCGHGE by approximately 200 tCO_2e over a 50-year POA and a LCC by about AUD 1,000, whereas the triple-glazed aluminium-framed option decreases LCGHGE by approximately 160 tCO_2e and increases LCC by about AUD 2,500 (refer to Figure 5.14). These results demonstrate the contribution of the framework to providing much needed understanding between environmental and economic building related decisions (one of the major barriers to the adoption of life cycle environmental optimisation).

The location of the building can also have a direct impact on the relationship between environmental and economic building performance. This was evident in the LCGHGE and LCC results for the insulation scenarios, where the R2 to R3 wall insulation upgrade was more suitable for the temperate Melbourne location and a ceiling insulation upgrade of R6 was of greater benefit for the subtropical Gold Coast location (from both a LCGHGE and LCC perspective). These findings are similar to studies such as Raji et al. (2017), Chastas and Theodosiou (2016) and Ramesh et al. (2010).

Providing a user with data pertaining to the relationships and trade-offs between economic and environmental factors, as outlined in this study's framework, is essential for better-informed building-related decisions (Braganca et al., 2014; Bierer et al., 2015).

These findings demonstrate the importance of location, sensitivity analysis and specific parameters, such as MSL and BSL, to assessing environmental and economic trade offs in building performance evaluation.

6.3.2. Affordability of greenhouse gas reduction design options

This study demonstrated that particular GHGE reduction options, like double-glazing (with a timber frame) or improved wall insulation (R3 glasswool), are not as expensive (in comparison to the other scenarios) when considered from a life cycle perspective. These options both result in a negative LCC cost per tonne of CO_2e reduced (refer to Figures 5.8 and 5.15).

Options like straw insulation (due to its high labour cost) and triple glazing (due to its high initial cost) still have a very high LCC compared to the other scenarios. This echoes the findings of studies by Jackson (2008), de Blas (2012) and Ellis (2009), who state that energy efficient solutions often have an increased cost associated with them (particularly the initial cost) and that 'green design' is perceived as expensive. Though these two options may come at an increased LCC, the sensitivity analysis demonstrated the fact that both straw and triple glazing consistently lead to a decrease in LCGHGE, regardless of what sensitivity parameter was selected (refer to Section 5.3.1.8 and 5.3.2.8). Hence, providing greater assurance to the user as to their LCGHGE reduction potential. Figure 5.8 indicated that for approximately AUD100, 1 tCO_2e reduction could be achieved through the use of straw insulation. Whether a user would be willing to pay an extra AUD100 for that LCGHGE reduction will be determined by their own personal preferences and goals.

Willingness to pay refers to what users may be willing to pay for reduced energy and GHGE building features, and incentives that may drive them to pay more for these features (lower energy bills, branding etc.) (Banfi et al., 2008; Zalejska-Jonsson, 2014). These incentives also refer to those in place by the government, such as the Renewable Energy Target (RET), which helps drive investment in renewable energy, or energy rebates (which encourages the selection of energy efficient products and services) (Australian Government, 2017). However there is still much work to be done to encourage homeowners to make use of these schemes, with states such as New South Wales, where the uptake of energy rebates by households have been below expectation (Nicholls, S, (2015)) with only about 12% of eligible households utilising these rebates. The Council of Social Service of NSW have called these rebates poorly targeted and too difficult to access (Nicholls, S, (2015). There is a need to provide a greater understanding as to what homeowners are willing to pay for these energy saving measures and encourage their uptake. Banfi et al. (2008) found that users are willing to pay between 3% and 13%, depending on the design feature selected. Another example from Chapter 5 is double-glazed timber-framed windows, which results in a decrease in LCC, and has a cost of negative 5 AUD/tCO_2e reduced. Whereas the option that actually leads to the greatest LCGHGE reduction, triple-glazed timber-framed windows, is only estimated to cost an extra 5 AUD/tCO_2e reduced (refer to Figure 5.15). Whether this cost is justifiable or not will depend on the user. Further research into what users are willing to select and willing to pay for the scenarios considered by such a framework is needed.

6.3.3. Importance of contextual characteristics

This study demonstrated the importance of considering the contextual characteristics when assessing the LCGHGE and LCC of buildings. The location of a building can affect the LCC results through inputs, including, price of materials and energy. LCGHGE results can be affected by inputs relating to the climatic conditions (which can influence the operational GHGE results) and energy mix, as confirmed by Dixit et al. (2010). The results of the application of the framework to the insulation scenarios clearly demonstrate the significance of this consideration (Section 5.3.1.6 and 5.3.1.7). In Figure 5.7 it can be seen that, as expected, all Gold Coast options have a lower LCC (as the average price of goods is about 7% lower, compared to Melbourne). The LCGHGE results were also affected with each location requiring different solutions more suited to its climate, such as improved wall insulation for temperate Melbourne and improved ceiling insulation (to decrease the heating loads) for sub-tropical Gold Coast. This emphasises the usefulness and capability of the developed framework as it can applied to different locations.

6.3.4. Importance of a life cycle perspective

The developed framework clearly demonstrated the importance of assessing a building's environmental and economic performance from a life cycle perspective. Several previous studies have based their LCC results on initial cost only (such as Langston and Langston (2008)), ignoring other life cycle stages like operational cost and replacement cost. Energy and GHGE related studies tend to be based on just the operational life cycle stage only (as discussed in Section 2.4.1), ignoring other life cycle stages like the initial embodied and recurrent embodied energy and GHGE.

An example of the importance of basing design decisions on a life cycle perspective can be found in the framework's application to the case study building's glazing scenarios (see Section 5.3.2.6). If a glazing option were to be chosen based on its IEGHGE only, single-glazed timber-frame windows would have been selected. However, triple-glazed timber-framed windows provide the greatest LCGHGE reduction potential. The same applies to the LCC perspective, where single-glazed timber-frame windows has the lowest initial cost (often the main basis of building related decisions (Jackson, 2008)), whereas triple-glazed timber-framed windows actually results in the greatest LCC reduction. By using the developed framework, assurance is provided that all relevant life cycle stages from both economic and environmental perspectives are included in building assessment and better-informed decisions can be made.

6.4. Dealing with uncertainties in life cycle study results

This study's framework demonstrated the large level of uncertainty surrounding LCGHGE and LCC results and the critical role of sensitivity analysis. Dixit et al. (2012b), Islam et al. (2015a) and Heijungs and Huijbregts (2004) have confirmed that life cycle studies (both environmental and economic) suffer from a large degree of uncertainty. This uncertainty stems from multiple aspects including the incompleteness of the evaluation method, the reliability of the data inputs, scope of the assessment and knowledge of the assessor, to name but a few.

These uncertainties were explored in Chapter 5 where a range of sensitivity parameters were applied to the results, as summarised in Table 6.2 below, in order to test the robustness of the framework and reliability of the results. These parameters were selected based on the sensitivity parameters most often explored in environmental and economic studies (as discussed in Section 3.6.3). This sensitivity analysis forms a critical component of the developed framework approach (Step 8, Figure 4.3) and of similar studies such as Stephan and Stephan (2016) and

Morrissey and Horne (2011). Some of the key variables affecting the uncertainty of the framework results, for both the LCGHGE and LCC, are discussed below.

Table 6.2 Sensitivity scenarios tested

Scenario (S)	Detail	Scenario (S)	Detail	Scenario (S)	Detail
S1	Period of analysis 100 years	**S2**	Original result	**S3**	Maximum GHGE (+20% OE, +40% EE)
S4	Minimum GHGE (+20% OE, +40% EE)	**S5**	Period of analysis 20 years	**S6**	Price of goods - 40%
S7	Price of goods - 30%	**S8**	Price of goods - 20%	**S9**	Price of goods - 10%
S10	Discount rate 3%	**S11**	Price of goods +10%	**S12**	Price of goods +20%
S13	Price of goods +30%	**S14**	Price of goods +40%	**S15**	Discount rate 10%

6.4.1. Uncertainty in life cycle greenhouse gas emissions results

The demonstration of the framework indicated the great difficulty involved in providing one single exact value for potential LCGHGE reduction across a wide range of building design options. Figure 6.4 demonstrates the large variability associated with the R3 wall insulation LCGHGE results for Melbourne. Sensitivity parameters S1 to S5 (as per Table 6.2) have been plotted with the minimum (min) and maximum (max) results. The sensitivity parameters that have the greatest influence on the LCGHGE results are POA. The 100 year POA (S1) achieves the greatest LCGHGE reduction and the 20 year option (S5) the least LCGHGE reduction. The next most significant parameters have to do with the amount of variability associated with embodied and operational GHGE results (±40% for embodied GHGE and ±20% for operational results), as previously suggested by Crawford (2013) and Juodis et al. (2009). These parameters have been discussed in more detail below.

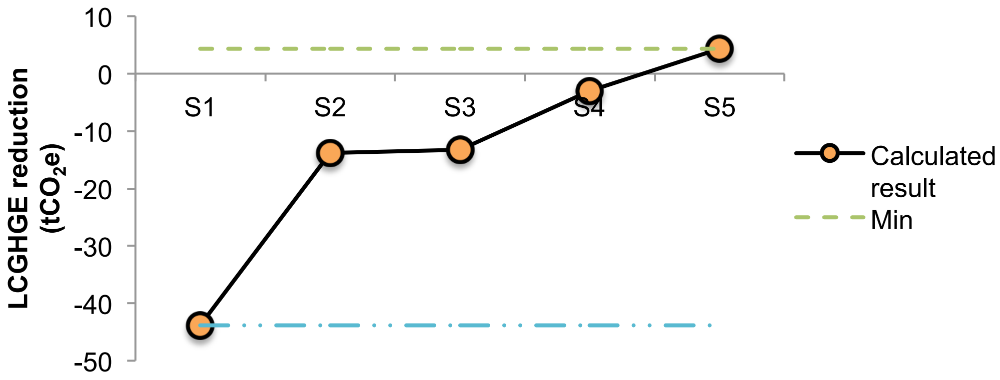


Figure 6.4 Variability in LCGHGE result for Melbourne's R3 wall insulation scenario

6.4.1.1. Impact of period of analysis

The developed framework demonstrated that POA has a significant effect on LCGHGE results. POA is often cited as a key sensitivity parameter influencing life cycle study results (Rauf and Crawford, 2013; Zabalza Bribián et al., 2011; Bull et al., 2014). Kneifel (2010) determined that POA affected both his LCC and LCGHGE results, and is an important determinant of the cost per tCO_2e reduced. His study found that the shorter POA had positive costs per tCO_2e reduced with the costs decreasing as the POA increases, similar to the findings of this study framework's demonstration results. The framework's LCGHGE results tended to favour the longer POA of 100 years over the shorter ones of 50 and 20 years. This is evident from the results in Section 5.3.1.8 and 5.3.2.8. In this study the POA has also been assumed to be the same amount of time as the building service life (BSL). It has become critical to acknowledge a shorter BSL, as the current trend in home ownership is leaning more towards shorter periods of time. One study states that the typical buyer of a single family home can be expected to stay for approximately 13 years before moving out and, on average, people move every 15 years (both values which are lower than the 20 year POA used in this study). Younger households tend to move more frequently (Australian Bureau of Statistics, 2011). This suggests that a shorter BSL is probably more realistic and has to be taken into account when undertaking life cycle studies.

The type of homeowner can also influence the results, for example, if a younger user is expected to live in the residential dwelling used in Chapter 5, an insulation option such as straw would be more ideal from a LCGHGE perspective as it does not increase upon the Base Case LCGHGE even with a 20 year POA (however it potentially comes at a higher LCC). R3 wall glasswool insulation would be better suited to a user who intends staying in the dwelling for a longer period of time. As length of homeownership is difficult to predict and that many dwellings will go through multiple users throughout their service life (Glink, 2016), it becomes critical to not only assess different POA in the sensitivity analysis but also to make it part of the main assessment (not merely an afterthought in the sensitivity analysis) so that the implications of a shorter and longer POA is well understood at an early stage in the design.

6.4.1.2. Impact of variability of greenhouse gas emissions results

This study demonstrated that the variability associated with LCGHGE results has a significant impact on the final result. The Path Exchange hybrid approach was selected to quantify the embodied GHGE for this study, as discussed in Chapter 3. Other approaches such as process and input-output analyses were not selected. For example process analysis, as discussed earlier, suffers from truncation error and neglecting several upstream impacts. However a large level of uncertainty and variability is associated with the data used, approximately ±40% (Crawford, 2004). This is due in part to the reliability, source and age of the data, to name but a few. The uncertainty in data is a major aspect plaguing life cycle studies and particularly embodied energy/GHGE calculations (Dixit et al., 2011). However, even with its large degree of uncertainty Path Exchange hybrid approach has been deemed appropriate for use due to its completeness when compared to process analysis (by far the most popular method in previous studies such as Anastaselos et al. (2011), Bovea and Vidal (2004) and Savino et al. (2017)), which has been found to have a underestimate by up to 87% (Crawford, 2008).

There has also been an ongoing effort to improve the reliability and completeness of the embodied GHGE and energy data with a rise in the number of hybrid based research projects such as this study and Teh et al. (2017). Voluntary embodied standards like Environmental Product Declarations (ALCAS, 2017), database generation projects such as the process based WRAP (UKGBC, 2017) and input-output based Industrial Ecology Virtual Laboratory (IELab, 2012) have also increased.

6.4.2. Uncertainty in life cycle cost results

The great difficulty encountered in providing one single exact value for the LCC for building design related options was demonstrated by the application of the framework to a case study building based on differing sensitivity parameters (see Section 5.3.1.8 and Section 5.3.2.8). Figure 6.5 demonstrates the large variability associated with the R3 wall insulation LCC results for Melbourne. Sensitivity parameters S1 to S15 (as per Table 6.2) have been plotted with the minimum (min) and maximum (max) results. The sensitivity parameters with the most significant impact on the LCC results are the DR (with the min LCC achieved when the DR is set to 3%, S10, and the max LCC when the DR is set to 10%, S15). The next most influenced parameter was the POG (S6 to S9, and S11 to S14). These parameters have been discussed in greater detail below.

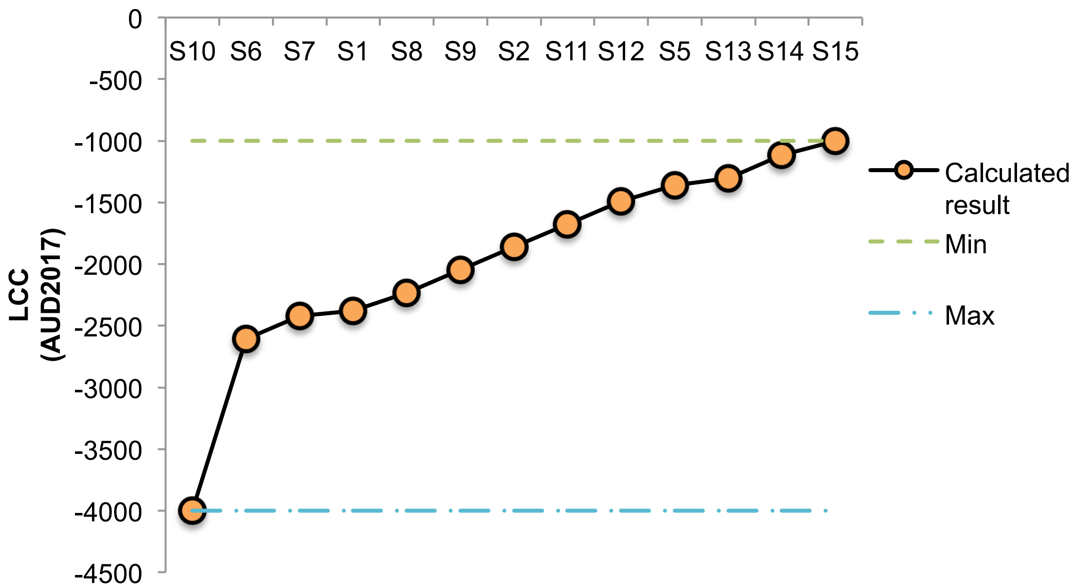


Figure 6.5 Variability in LCC result for Melbourne's R3 wall insulation scenario

6.4.2.1. Impact of discount rate

LCC studies, especially ones that use the NPV approach, are significantly influenced by the DR (Gallant, 2017). The results in Chapter 5 favoured a lower DR of 3%, providing the minimum LCC across all residential results regardless of the building elements being assessed. The higher DR of 10% increased the LCC. LCC assessment requires a substantial number of assumptions, as it entails predicting the future (how much materials will cost in the future, how the DR will be affected in the future and the like), which is a difficult exercise and involves a great level of uncertainty (Gallant, 2017; Ristimäki et al., 2013). Basing the LCC results on just one DR is not recommend and a range of DR should be used (Anand and Apul, 2011; Roebuck et al., 2011; Ristimäki et al., 2013). Ristimäki et al. (2013) states that using a high DR will emphasise the near future and a low DR the distant future, which is necessary for frameworks such as this that span over several years. Similar to the POA input parameter, the inclusion of DR variations (a low, medium and high range) be included in the main part of the framework analysis (not just in the sensitivity analysis) is suggested as the user must to be made aware of the possible range of LCC results resulting from varying DR values.

6.4.2.2. Impact of price of goods

After DR, the framework demonstration results found POG to have the most significant impact on both LCC and LCGHGE results. The POG decrease (i.e. -10% to -40% of the original price of materials) particularly influenced the LCC results of these scenarios generally representing a higher initial cost, such as EPS and straw insulation (which has a higher initial cost that glasswool R2 insulation) or triple-glazed timber-framed windows (which have a higher initial cost than single or double glazed window alternatives). There is also great variability when it comes to the POG, with different manufacturers providing different costs, and the variability in the cost of labour. For example, straw insulation is a low cost material but requires labour-intensive construction techniques. Labour costs can vary widely as straw bale homes are presently unregulated and the builder will have to demonstrate that the house meets the building code requirements, which can increase the hourly labour rate (BUILD, 2017; Downton, 2013). Leusch (2011) stated that a straw bale house could cost approximately 28% less than a conventional house. In contrast, Green (2010) found straw bale houses to be 15% more expensive than standard brick veneer houses. Kairl (2014) and Ausbale (2017) also found straw bale houses to cost more than conventional homes. The price per straw bale (which is roughly 0.3m^2), in 2017, varies between AUD5 to AUD9 (Ausbale, 2017). Based on an average of AUD7 per bale, it equates to approximately 21 AUD per m^2. This excludes labour costs (which can potentially results in an increase of 50% (Leusch, 2011)). The significant amount of variability surrounding the cost of straw insulation has to be considered when interpreting the results.

For the LCGHGE, the POG influenced factors such as the cost of energy, which will probably change over the expected lifetime of the building. However, only one energy price was used in this study for the POA due to the unpredictability of future energy trends, and will have to be an updatable input parameter in future development of the integrated frameworks. The embodied GHGE results are also influenced by the POG due to the use of cost data within the Patch Exchange hybrid approach (refer to the calculations in Section 3.2.6). The initial embodied GHGE will be affected, as the price of the building will increase as a result of the POG increasing. The recurrent embodied GHGE will increase due to the POG increasing (as it will be more costly to purchase the necessary items for replacement).

The sensitivity of this was tested in Figure 6.6, where the 1997 POG were compared against a price increase of 40%. Proportionally the results vary only slightly, where the first pie chart (Figure 6.6) has the original results (where the IEGHGE is roughly 10% of the LCGHGE and REGHGE 8%) and the second pie chart depicting the change if the POG increases by 40% (where the IEGHGE increases to 12% and REGHGE increases to 10% of the LCGHGE). Another cost aspect worth considering is the fact that the 2017 price of materials had to be converted to 1997 prices (in order to reflect the 1997 energy based input-output data used) (refer to Section 3.2.6.1). If 2017 prices were to be considered for the embodied calculations (therefore without conversion to 1997 prices), proportionally the LCGHGE results differ very slightly in Figure 6.6. Therefore, based on this study, it can be concluded that providing that all the prices in an assessment are based on the same year or the same cost percentage increase, proportionally, the results will not be significantly affected. The sensitivity of this will have to be the subject of further research in the future.

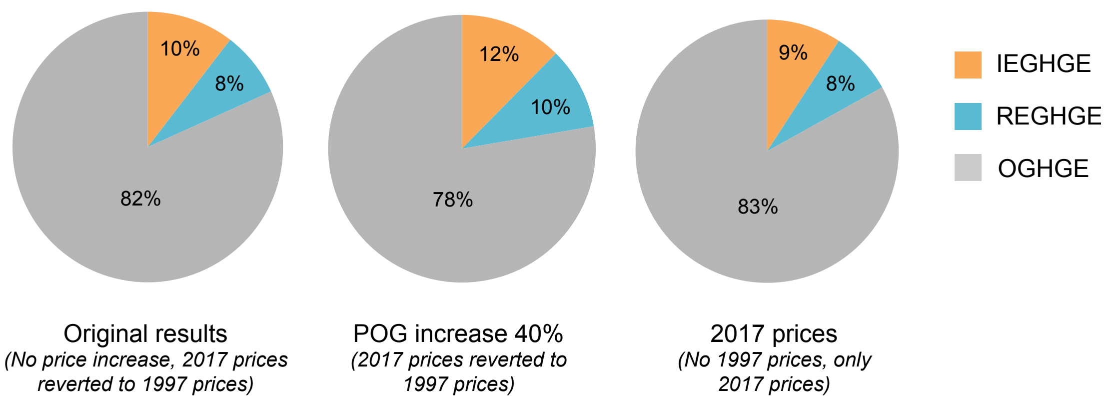


Figure 6.6 Effect of price variation on life cycle greenhouse gas results

[GHGE: Greenhouse gas emissions, IEGHGE: Initial embodied GHGE, REGHGE: Recurrent embodied GHGE, OGHGE: Operational GHGE, POG: Price of goods]

The uncertainty regarding the POG input parameter will also be greatly reduced once the actual costs for the materials and labour are known which can then be accurately modelled in the assessment. However, as the developed framework is intended to be used at an early stage in the design process, the actual price of items will most likely not be known at this early stage, thus an estimation will have to be made. It is recommended that the framework's cost data be adjusted once more information about material suppliers becomes available, to ensure that results are as accurate as possible.

Based on the level of uncertainty attached to both LCGHGE and LCC results obtained from the framework demonstration, it is suggested that the key sensitivity parameters (i.e. POA and DR) be included in the main body of the framework results, not just as part of the sensitivity analysis towards the final stages of the building evaluation (as is so often the case). This forms part an integral part of this study's, and any future, integrated environmental and economic framework development.

The inclusion of sensitivity parameters has been visualised for the application of the framework to the insulation scenarios for Melbourne, as shown in Figure 6.7. All insulation options are plotted according to the possible minimum and maximum values for both LCGHGE and LCC. This will help ensure the user of the possible best and worst case scenarios, from the start of the project, which will contribute to more informed decision-making.

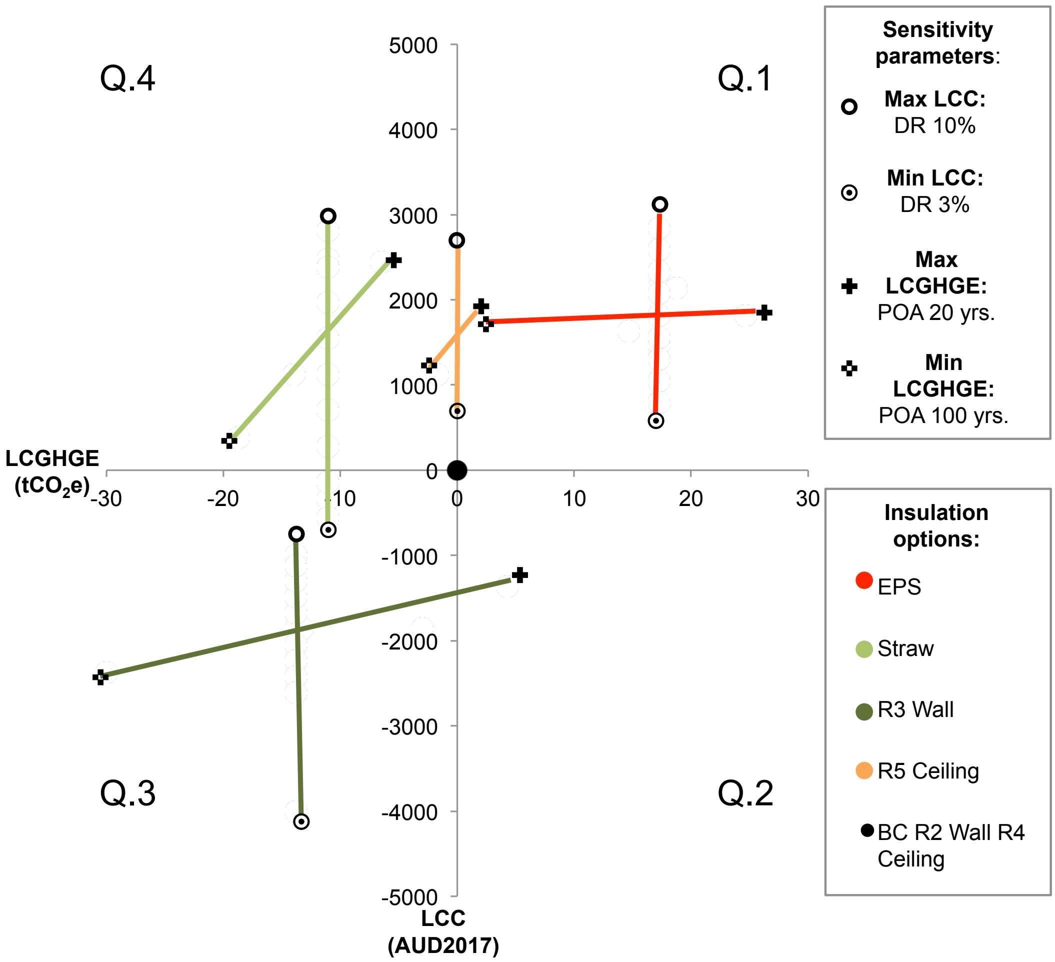


Figure 6.7 Minimum and maximum LCGHGE and LCC for case study insulation scenarios in Melbourne

6.5. Implications for the discipline

The developed environmental and economic framework that formed part of this study provided a significant contribution to the rapidly evolving field of integrated building performance analysis. As stated in the studies by Goh and Sun (2015) and Gluch and Baumann (2004), the integration of both environmental and economic building assessments, especially from a life cycle perspective, is a key future research area in building performance evaluation. They emphasised the need to create new tools and methods that would integrate these two assessments, improve understanding thereof and involve people in the decision-making process. This study has contributed to this key future research area, by providing a guide for the development of an integrated form of environmental and economic assessment can be developed in the form of a comprehensive framework, that incorporates the user in the decision-making process, and by then applying it to an actual case study example to demonstrate its potential. This has been achieved by providing a detailed step-by-step guide to the integration of environmental and economic building performance evaluation in terms of LCA and LCC, the decision-support frameworks that could assist in this integration, the quantification techniques available for environmental and economic analysis, the various pre-defined and user defined input parameters must be included and the visual outputs that could be used to visualise the results (as discussed in Chapter 3 and Section 6.2.2 above).

The results in Chapter 5 have also emphasised the critical importance of incorporating sensitivity parameters in an integrated environmental and economic framework. The significance of the uncertainty in life cycle studies results has been discussed above in Section 6.4 and it has been suggested that these key parameters be included in the main body of results (as per Figure 6.7), and not merely as an afterthought (or not included at all) as often happens in building assessments.

A further significant contribution to the life cycle building evaluation discipline is found in the example of utilising and applying a more comprehensive form of LCGHGE and LCC analysis that was provided as part of the developed framework. This was achieved by using the Path Exchange hybrid approach for embodied analysis, NPV approach for LCC and OAT analysis for sensitivity analysis. This has been discussed in more detail in Section 6.2.3. This constitutes a critical requirement of this study's framework demonstration, and any future framework development, in order to ensure that design team members can base their decisions on better-informed and reliable results.

The importance of continued improvement of the reliability of data and quantification techniques has been established in this study's sensitivity analysis (Chapter 5 and Section 6.4.1.2). There is still much room for improvement in such data, to decrease the level of uncertainty associated with LCGHGE results. More reliable results will let industry more confidence in the use of the data and the developed framework. This could in turn increase the uptake of building assessments that integrate environmental and economic performance, also from a life cycle perspective.

6.6. Implications for the industry

The developed framework has several implications for the built environment industry. Firstly, it facilitates simultaneous communication of environmental and economic results side by side. The framework integrated environmental and economic building performance evaluation into a single comprehensive form of analysis (Chapter 4) and demonstrated the visualisation of the integrated results (Chapter 5) to communicate the findings. This is crucial as design team members must be able to communicate their building analysis to clients in an effective and relatable manner. Most people do not comprehend numbers and tables as easily as visual results, as discussed earlier. By providing design team members with visual outputs, as associated with the developed framework, and as demonstrated in Chapter 5, both environmental and economic building assessment can be integrated more effectively into the overall design process. The importance of these visual results to the decision-making process was discussed further in Section 6.2.4 above. The visualisation of results provides a much-needed format as most previous environmental and economic frameworks and studies did not provide such outputs. Providing a visual format of results facilitates users' interpretation and communicates the trade-offs between economic and environmental results more effectively.

Secondly the developed framework addresses one of the major barriers preventing the adoption of life cycle analysis within industry (as discussed in Section 2.2.4), namely the uncertainty associated with the financial cost of life cycle environmental building optimisation. The developed framework provided much needed understanding for the possible economic implications of LCGHGE optimisation (as discussed in Section 6.3.1). This will enable industry to communicate the potential economic cost of environmental design scenarios more clearly to clients. Addressing these economic uncertainties could increase life cycle based studies.

Thirdly, the developed framework's results have potential implications for policy. As stated before in Chapter 2, there is no mandatory legislation requiring the assessment of buildings from a life cycle perspective. However the use of such a framework can potentially influence policy aspects, such as energy rebates (Australian Government, 2017), emission reduction fund (Department of the Environment and Energy, 2017b), carbon farming initiative (Department of the Environment and Energy, 2017a) and building regulations (Australian Building Codes Board, 2015a). The framework could help illustrate which options (whether it be for buildings or larger scale urban or rural developments) lead to significant LCGHGE reduction and what the economic implications (and incentives) of these scenarios could be. This could affect the amount of rebate, for example, associated with these lower GHGE design scenarios. By way of example, the application of the framework to the insulation scenarios for the case study building demonstrated that straw insulation leads to significant LCGHGE reduction notwithstanding greater initial cost, which resulted in a higher LCC. The provision of a rebate for straw insulation could decrease the initial cost to the user, which in turn could decrease the LCC, making this a more attractive insulation option to users. It could also identify the design options that may essentially form part of mandatory building regulations. For example, at present R2 wall insulation is a residential building requirement. However, this framework's insulation scenarios application demonstrated that improving the wall insulation to R3 has a significant beneficial influence on the buildings LCGHGE, and should possibly form part of future building regulations. Current international policies, such as energy performance of buildings directive (EPDB), tend to focus on the operational life cycle stage. However this study demonstrated that the IEGHGE can be as high as 30% and the REGHGE as high as 20% (for the EPS insulation scenario) of the whole life GHGE. Other studies have found the embodied life cycle stage to account up to 97% of a building's LCGHGE (Chastas and Theodosiou, 2016). This emphasises the fact that these embodied life cycle stages can no longer be ignored in building performance assessment and policy provision. If studies like this can continue to demonstrate the importance of an integrated life cycle perspective, and demonstrate how drastically results can differ when all life cycle stages are taken into account (as discussed in 6.3.4), the critical need for inclusion as part of policy development will become more evident.

Lastly, as the developed framework uses the quantification techniques and methods already associated with the LCA and LCC practice (see Chapter 3), it does not require any additional training to use. Provided that design team members already have some familiarity with these established methods, the framework is easy to use and the provision of the step-by-step guide, the input parameters and calculation methods (as described in Chapter 3 and 4), provides additional guidance to the potential user in the successful application of the framework. The visualisation of results (as illustrated in Chapter 5) were also generated by popular tools, including Microsoft Excel, which is regarded as one of the most popular industry used tools (Robarts, 2014), and therefore requires no additional training.

6.7. Limitations of the framework results

This study has developed a novel and comprehensive integrated environmental and economic framework and has demonstrated its potential by the application thereof to built environment related examples. However, as with any research project there is a range of limitations to be aware of when interpreting the results of this study.

6.7.1. Data

A limitation of the demonstration of the framework is the fact that the embodied GHGE quantification relied on a 1997/1998 energy-based input-output model (the latest available at the time of the research). It is acknowledged that this data is some 20 years out of date at the time of publication and changes and technological improvements have most likely taken place, which could influence the accuracy of the LCGHGE results. It is recommended that the embodied energy coefficients be updated with more recent data once it becomes available. The data used for the LCGHGE and LCC quantification process is also only applicable to Australia and would have to be customised for other countries to make the findings more context specific. Some of the data has also been simplified, for example the fact that the same DR, energy demand, recurrent costs and emission factors is expected to be used throughout the lifespan of the building. This however can potentially change over the next few years due to technical advancements in the energy field, or other factors such as fuel scarcity (IPCC, 2014). Limitations associated with recurrent costs are also inherent in LCC studies. It is difficult to predict how these items will change in the future (some studies have recommended certain projection scenarios that can be included in the model, including Pesonen et al. (2000), but this falls outside the scope of this study). Updating the data in the framework as soon as more recent data becomes available. It should be noted that the data for the framework is not rigid and may be replaced with any suitable data. Chapter 3 provides an example of the suggested quantification methods and pre-defined input variables that may be used and Chapter 5 provides an example of the type of user defined data that may be used. However the input variables and suggested data is based on the more comprehensive and reliable methods of Path Exchange hybrid and NPV, and major adjustments to the data will compromise the accuracy of the framework results.

6.7.2. Case studies

The study uses a limited number of case study examples to demonstrate the use of the framework (one building, two building elements and two locations). Case studies are popular in life cycle and energy efficiency studies, for example Beyond Zero Emissions (2013), Schwartz et al. (2016) and Bull et al. (2014). However, case study research has been subject to criticism as it is usually based on a small number of subjects and scientific generalisation and statistical relevance is not warranted (Yin, 1994; Tellis, 1997; Zainal, 2007). This study aimed to help counteract this disadvantage by examining two different locations and two different building elements. The framework demonstration results are not based on a single case exploration, as in previous studies (Gu et al., 2008; Hamdy et al., 2013; Schwartz et al., 2016), which is often cited as a disadvantage of case study research (Yin, 1994). The inclusion of more case studies, from different contexts and typologies, in future research is recommended for a more robust framework. Another limitation that can be addressed in future studies is to include more building components in the embodied GHGE analysis (other than those listed in Table 3.2), such as services (plumbing, electrical etc.) and internal fittings. Even with its associated disadvantages case study research provided an ideal platform to help simplify and investigate a complex problem (that of the integrated assessment of both environmental and economic performance of buildings) and base the study's data on 'real-life' environment (Yin, 1994). This approach also isolated a phenomenon from its context and focused on a limited number of variables (Zainal, 2007), which was beneficial to time (as it was less time consuming as the scope could be narrowed) and reduced the data requirements of this study (due to the limited scope). A case study approach has also been deemed appropriate for the preliminary stages of an investigation (Abercrombie et al., 1984), which complements the nature of this study. Making the findings of this study more statistically relevant and applicable to a wider field require the inclusion of more case studies in any future research.

6.7.3. User behaviour

The uncertainty in user behaviour has not been taken into account in the developed framework. Several studies have explored the impact of user behaviour on LCA studies such as Pettersen (1994), Brunklaus et al. (2010) and Gram-Hanssen (2010).

From an operational GHGE perspective users have an influence, for example, on the thermal comfort settings and energy use patterns of a building, which can alter the overall energy demand of the building. From an embodied GHGE perspective, material and product selection are based on users' personal preferences, resulting in an increase or decrease in initial embodied GHGE (depending on the selection of either energy intensive or recycled materials, for example). The selection of materials can also have an impact on the frequency of replacements, which in turn could affect the recurrent embodied GHGE. LCC is also affected by user preferences, where final selection of materials and energy supplier can have an influence on the LCC results (as some materials will have a higher or lower initial cost, for example). A study by Gram-Hanssen (2010) has demonstrated the influence of user behaviour on energy results, finding that the operational energy use of different households living in the same dwelling can differ by more than 300%.

The framework utilises average energy use based on information available in Australian Bureau of Statistics (2010) and Beyond Zero Emissions (2013). It is suggested that more energy use scenarios must be included in future research.

7.

Conclusion

It has become critical to address the growing concerns around climate change and to mitigate its effects through actions like decreasing building related energy demand and greenhouse gas emissions (GHGE). This mitigation must not only focus exclusively on one life cycle stage, namely operational, as has been the case thus far, but rather from a life cycle perspective. Notwithstanding the availability of environmental assessment tools such as life cycle assessment (LCA), the adoption of life cycle environmental optimisation building design has been slow as a result of a number of barriers. One such barrier is the uncertainty attached to the financial implications of this life cycle energy and GHGE reduction. Regardless of the availability of financial life cycle tools, such as life cycle costing (LCC), there is a continued tendency to focus only on initial cost, or to perform LCA and LCC in isolation of each other. This restricts the ability of building designers and users to consider important relationships and trade-offs between economic and environmental performance in the evaluation of different building design options.

The study successfully achieved the research aim of developing a framework for the integrated optimisation of the environmental and economic performance of buildings. It incorporates all life cycle stages and provides an ideal platform from which to investigate the suitability of design options in the reduction of the GHGE of built environment. This study developed the integrated framework by addressing the gaps of previous environmental and economic studies (including the lack of transparent calculations and inputs, the lack of graphical outputs, the lack of building scale analysis). This study provides the first integrated environmental and economic framework that addresses all such gaps. These gaps also provide a road map for future environmental and economic framework development.

In order to address the first Research Question of identifying the most appropriate environmental and economic decision-support approaches, this study drew upon the strengths of existing frameworks. The techniques (i.e. step by step guides) and methods already associated with popular environmental and economic evaluation approaches, namely LCA, LCC and other decision-support frameworks, such as the multi-criteria decision-making (MCDM) framework were adopted. This included providing the approach (steps to be followed by users for the completion of an integrated environmental and economic assessment) and describing other aspects like prospective visual output devices. The framework's development also included a detailed overview of the quantification techniques utilised in the economic and environmental assessment together with the various input parameters associated with these techniques. This addressed Research Question 2 (What are the most appropriate environmental and economic quantification techniques?) and Research Question 3 (How can the environmental and economic assessment of buildings be integrated into a single framework for comprehensive building evaluation?).

The framework of this study addresses one of the key gaps impeding most previous studies by providing a more comprehensive form of environmental assessment, through the use of Path Exchange hybrid method. It also provides a more comprehensive form of LCC assessment with the inclusion of the Net Present Value (NPV) technique, which takes the time value of money into account. The integrated framework is further enhanced through a detailed sensitivity analysis, which helps to address the significant level of uncertainty associated with life cycle studies. The framework further integrates environmental and economic results into one single unit and into a single visual output to facilitate interpretation. In addition, the framework allows for user personal preferences (through the transparent and unbiased manner of representing results) and is applicable to early stage design (through the selection of parameters typically available at the beginning of the project). This results in the provision of a more sophisticated and comprehensive form of integrated environmental and economic assessment of buildings, compared to most earlier studies.

The potential of this framework was further demonstrated by the application thereof to a case study building, namely a detached residential dwelling, two different locations (Melbourne and Gold Coast) and two different building elements (namely insulation and glazing) to highlight its flexibility, its applicability to building scale evaluation and the range of results possible. For this demonstration, the impact category of global warming potential was selected as part of assessing the case study's LCGHGE. This demonstration also included comparing the results to similar studies, therefore emphasising the framework's comparability and reliability. The robustness of the framework was further explored through detailed sensitivity analysis, which identified a range of factors that had a significant impact on the results but did emphasise that the ranking of the assessed options do not change regardless of the sensitivity parameter selected. Through the development of the framework approach and demonstration of the type of outputs that can be expected by its use, Research Question 3 was fully addressed: How can the environmental and economic performance of buildings be integrated into a single framework for comprehensive building evaluation?.

This study helped to contradict the perception that GHGE reduction solutions are not always the most expensive solutions, as options such as increasing the wall insulation actually resulted in a negative LCC. For options that result in a positive LCC, like straw insulation or triple glazing, a decrease in LCGHGE could be realised for an additional cost per tonne of CO_2e reduced. However, the suitability of this amount would be based on the user's willingness to pay and would have to conform with their personal preferences. The results of this study also confirmed that strategies for decreasing the LCGHGE, for example selecting more robust materials with longer service lives, could also benefit the LCC performance of a building.

Another aspect that this study addressed is the great level of uncertainty associated with life cycle studies and the effect of this uncertainty on the developed framework's results. Sensitivity parameters like period of analysis (POA), discount rate (DR) and the uncertainty associated with embodied and operational energy and GHGE quantification methodologies, have a significant impact on the final results. This emphasises the great amount of difficulty in providing a single exact value for either life cycle environmental or economic optimisation. It was therefore concluded that in order to ensure that the possible variability of results be transparent to the framework user, the results be presented in a range (i.e. minimum and maximum). For life cycle environmental results, the POA had the most significant influence on the results. To take the uncertainty of the expected service life of the building and the type of possible users (with younger homeowners tending to live in a house for a shorter amount of time than older homeowners or families) into account, low, medium and high POA scenarios should be selected and included in the main body of the framework results. For life cycle economic results, DR had a similar impact on results, and accordingly low, medium and high DR values should be incorporated to take the great level of uncertainty associated with predicating future costs into account. This range of results therefore forms part of the main framework, until further development in the life cycle environmental and economic methodologies and associated data sets take place that can help reduce the amount of uncertainty. However, even if this level of uncertainty is reduced, the prevailing uncertainty of user behaviour must be taken into account. As often the case, the intended use of the building through design does not translate into the actual use with other inputs beyond cost and GHGE influencing behaviour. This suggests that possible future considerations should be included in the development of the framework, including a range of possible user behaviour scenarios (for example, high and low energy users and different occupancy schedules).

The developed framework also suffers from limitations including the fact that the demonstration of the framework and consequential findings are only based on a small number of case studies. The data is also applicable to Australia only and several simplifications (such as using only one energy price value for the whole period of analyses) are assumed. These limitations can be addressed in future research as outlined below.

Regardless of the limitations of this framework and the great level of uncertainty surrounding life cycle studies, this study did succeed in developing a sophisticated and comprehensive integrated framework, demonstrated the possible trade-offs between economic and environmental considerations of different building design decisions and identified the key sensitivity parameters that have to be included in future integrated environmental and economic framework development. This study's contribution to knowledge is outlined below.

7.1. Contribution to knowledge

This research provides a significant contribution to knowledge in the following areas:

- Developed a novel life cycle environmental and economic framework for integrated building performance analysis.
- Provided an example of the use of comprehensive environmental and economic building performance quantification techniques within the developed framework, including: Path Exchange hybrid approach for embodied GHGE quantification, NPV for LCC quantification and One-At-a-Time approach for sensitivity analysis.
- Demonstrated the application of such an environmental and economic integrated framework to a built environment case study building and the value of the framework results in informing the decision-making process.
- Provided examples of the various visual outputs that can be used to better communicate the relationship and trade-offs between life cycle environmental and economic performance of buildings.
- Provided a means for industry (architects, engineers and sustainability specialists) to simultaneously communicate environmental and economic results, side by side, to their clients. This results in better-informed building and provided much needed clarification regarding the uncertainty of the financial cost of LCGHGE reduction.

- Addressed one of the major barriers presently plaguing life cycle environmental design optimisation, being the financial uncertainty associated with environmental improvements strategies.
- Identified several key sensitivity parameters that influence integrated life cycle environmental and economic performance and the range of result variability.

7.2. Further Research

While this research has developed a comprehensive framework for the integrated optimisation of the environmental and economic performance of buildings, further research may be pursued in various areas that fall outside the scope of this work. These include, but are not limited to, the consideration of other environmental impacts (such as water), the inclusion of more case studies (such as other building typologies and elements) and the inclusion of other user preferences other than cost and GHGE (such as comfort).

Though energy and GHGE provide ideal platforms from which to help mitigate building related environmental impacts, the scarcity of water and the embodied energy related to water harvesting and management systems are gaining importance in built environment design. There is thus a need to expand upon the framework's capabilities and to include an investigation into the life cycle water requirements associated with building design. The frameworks sensitivity analysis could also be expanded further and future research with the inclusion of more parameters such as the decarbonisation of energy, different fuel mixes or high and low energy consumption by users, for example. The inclusion of more parameters into the framework can expand its capability, adaptability and applicability to built environment related design issues.

The application of the framework incorporated two different cities and two different building elements. However, the number of case studies presented as part of this application is remains limited and in order to increase its statistical relevance and broader applicability, more case studies have to be included in future research. This will ensure that the framework is applicable across a broader range of building typologies and design variations.

As alluded to earlier, user behaviour has a significant influence on the actual energy use and GHGE of a building. There is also a tendency for users to base their building design selections on parameters, other than GHGE and cost, including aesthetics, material availability, acoustic performance and fire resistance, to name but a few, and other cultural considerations (relating to aspects such as heritage or vernacular traditions). Future development of the framework has to take this into account in order to make the framework applicable to the widest range of project needs possible as there is no one ideal solution for all users.

Further research with regards to life cycle practice is necessary in order to reduce the great level of uncertainty and unreliability of the data and methods in this field. An agreed upon method will help reduce the amount of variability of results while improved quantification techniques and data sources can help reduce the large variability range (for example the ±40% associated with embodied GHGE data).

By addressing these various aspects, the development of the life cycle environmental and economic integrated optimisation of buildings can continue.

7.2.1. Potential improvements to the integrated framework.

The improvements outlined hereunder are recommended for the environmental and economic framework, as detailed in Figure 7.1. Firstly the limitations of this study have to be addressed such as the inclusion of more case studies and expansion of the input parameters (for example, the consideration of more sensitivity parameters, environmental categories and scenarios). This will make the framework applicable to a broader range of building related design decisions. The next step would be to test the output of the integrated framework on the intended user group (architects, engineers and sustainability specialists). This will establish whether the framework provides suitable and usable outputs (such as the graphs and results). The step thereafter would be to use the input from the user group test phase and adjust and refine the framework outputs. This will ensure that the framework has been adjusted to the user needs, making it as user-friendly and industry relevant as possible. The final step would be to translate the integrated framework into a dynamic user-friendly tool with a possible web interface to potentially increase the uptake of its use and promote its accessibility to a wider audience. An ongoing further research element would be continuous updates to the tool, with the most recent data inputs, in order to enhance its accuracy and reliability.

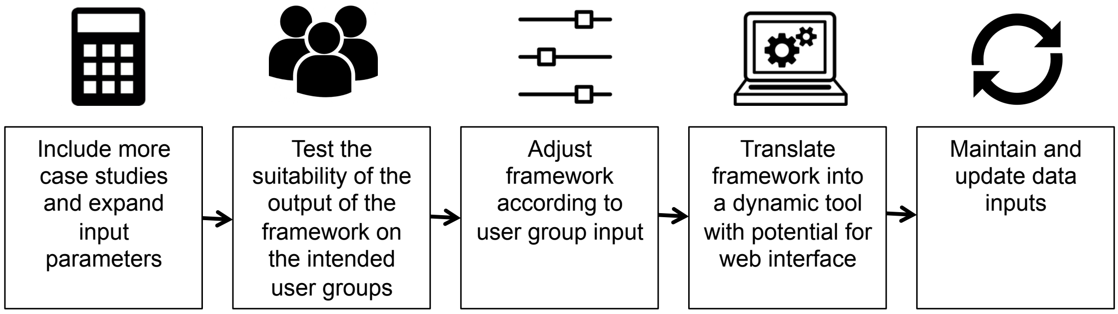


Figure 7.1 Potential improvements and further research for integrated environmental and economic framework development

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Appendices

Appendix A: Background

Review of previous life cycle analysis and life cycle cost studies

Legend												
	✓: Included	?: Not provided/ unclear	C: Cooling	DHW: Domestic hot water	IEE: Initial embodied energy	LCC: Life cycle cost	LCEA: Life cycle energy analysis	LCGHG: Life cycle green house gas analysis	NPV: Net present value	P: Process	REE: Recurrent embodied energy	Oper: Operational
	✗: Not included	A: Appliances	CBA: Cash benefit analysis	H: Heating	IO: Input-output	LCA: Life cycle analysis	L: Lighting	MFCA: Material flow cost accounting	OE: Operational energy	PP: Payback period	IO-H: Input Output Hybrid	Maint: Maintenance

Table A.1 Review of previous life cycle analysis and life cycle cost studies

Source	Title	LCA							LCC					Output	Strengths	Weaknesses
		LCEA/ LCGHGE	LCI Method	OE inclu-sions	System boundary				Method	System boundary						
					IEE	REE	OE	Demo		Initial	Oper.	Main.	Demo			
Anastaselos et al. (2009); Greece	Assessment **tool** for the energy, economic and environmental evaluation of thermal insulation solutions	LCEA	P	H C L DHW	✔	✔	✔	✗	?	✔	✔	✗	✗	Results separated and presented in bar charts and tables	Detailed material and building level evaluation	Upstream impacts excluded due to process data; Results not integrated.

Source	Title	LCA							LCC					Output	Strengths	Weaknesses
		LCEA/ LCGHGE	LCI Method	OE inclu-sions	System boundary				Method	System boundary						
					IEE	REE	OE	Demo		Initial	Oper.	Main.	Demo			
Bierer et al. (2015), Germany	**Model** for integrating LCA and LCC	LCEA	?	?	✔	✔	✔	?	MFCA	✔	✔	✔	?	No output specified	None identified applicable to this study's research theme	MFCA mainly for material level not building level analyses; Predominant focus on monetary cost ; Data inputs and system boundary unclear
Bovea and Vidal (2004), Spain	Integrated **model** for environmental impact, costs and customer valuation	LCEA	P	?	✔	?	?	?	?	✔	?	?	?	Environmental impact and cost separately presented in bar graphs	Provides a detailed breakdown of the 'stages' of the analysis (for example stage 1, initial analysis with LCA; stage 2 generation of alternatives etc.); Includes willingness to pay	Results not integrated.; Upstream impacts excluded due to process data.; Product case study not building; Not suitable for early stage design

Source	Title	LCA							LCC					Output	Strengths	Weaknesses
		LCEA/ LCGHGE	LCI Method	OE inclu-sions	System boundary				Method	System boundary						
					IEE	REE	OE	Demo		Initial	Oper.	Main.	Demo			
Bull et al. (2014); UK	Life cycle cost and carbon footprint of energy efficient refurbishments to 20th century UK school buildings	LCGHGE	P	H C L A DHW	✔	✔	✔	?	NPV	✔	✔	✔	?	Tables provide energy savings and NPV results separately.	Material assumptions and simulation inputs clearly stated; Calculations provided Regression analysis included	Does not provide a framework, method or tool that can help integrate LCA and LCC; Focus on exemplar buildings (buildings that are already low energy) and not typical buildings. Process data
Deng et al. (2008), China	A **framework** for the integration of LCA and LCC to eco-balance for mechanical product design	LCEA	IO	?	✔	✔	✔	✗	NPV	✔	✔	✔	✗	Table with 'improvement degree' and 'integrated benefit index'	Detailed framework outline diagram	Weighting and scaling factors not explained; Lack of graphs; Truncation error due to IO data; Appropriate for product assessment not building; Not suited for early design phase

Source	**Title**	**LCA**							**LCC**					**Output**	**Strengths**	**Weaknesses**
		LCEA/ LCGHGE	LCI Method	OE inclu-sions	System boundary				Method	System boundary						
					IEE	REE	OE	Demo		Initial	Oper.	Main.	Demo			
Ding (2005), Sydney	Multi-criteria sustainability index **model**	LCEA & LCGHGE	IO	?	✔	✔	✔	?	NPV	✔	✔	✔	?	Graphical matrix with financial return; energy consumption, environmental impact and external benefits. Results not integrated into this though.	Allows for the use of personal parameters (for example investors might be more concerned about value of money whereas the users quality of life.	Weighting and scaling factors not explained; Truncation error due to input output data
Gu et al. (2008), China	Life cycle green cost assessment **method**	LCGGHGE	P	?	✔	✔	✔	✗	NPV	✔	✔	✔	✗	LCA and LCC results provided in separate tables.	Clearly links each LCA phase to LCC phase	Results not integrated; Weighting and scaling factors not explained; Equations and data sources not provided Process data
Hamdy et al. (2013), Finland	Multi-stage optimisation **model** for cost optimal and nearly zero energy building solutions	LCEA	?	H C L A DHW	✔	✔	✔	✗	NPV	✔	✔	✔	✗	Graphs with 'difference in LCC' on y-axis and 'primary energy consumption' on x-axis	Carried out a detailed sensitivity analysis Integrated results	Not all data inputs and methods specified; Absolute value of LCC not calculated, only the difference in savings from one option to the next.

Source	Title	LCA							LCC					Output	Strengths	Weaknesses
		LCEA/ LCGHGE	LCI Method	OE inclu-sions	System boundary				Method	System boundary						
					IEE	REE	OE	Demo		Initial	Oper.	Main.	Demo			
Heijungs et al. (2013), The Netherlands	A computational **framework** life cycle sustainability analysis	LCEA	?	?	✔	?	✔	✔	?	✔	✔	?	✔	No output specified	Includes demolition	Data inputs unclear; Results not integrated; Weighting and scaling factors not explained Complex linear equations
Hoogmartens et al. (2014), Belgium	LCA, LCC and CBA sustainability assessment **tool** applied to 'end-of-life automotive glass'	LCEA & LCGHGE	?	?	✔	?	✔	?	NPV	✔	?	?	✔	No output provided.	Includes social sustainability; Considers time value of money ; Focus on recycling of materials	Results not integrated; Data sources, equations and methods not provided; Framework only theoretical and not applied to generate results.
Huppes and Ishikawa (2005), The Netherlands	A **framework** for quantified eco-efficiency analysis	LCEA & LCGHGE	?	?	✔	?	✔	?	CBA	✔	✔	?	?	Graphical: Environmental burden on the X-axis and economic value on the Y-axis	Includes willingness to pay Includes micro-level eco-efficiency of technologies and macro level eco-efficiency of society.	Very theoretical and not applied to a practical context/ case study; Several steps and levels of evaluation that might lead to time-consuming analysis Weighting and scaling factors not provided.

Source	Title	LCA							LCC					Output	Strengths	Weaknesses
		LCEA/ LCGHGE	LCI Method	OE inclu-sions	System boundary				Method	System boundary						
					IEE	REE	OE	Demo		Initial	Oper.	Main.	Demo			
Kneifel (2010), USA	Life cycle carbon and cost **analysis** of energy efficiency measures in new commercial buildings	LCGHGE	P	H C L A DHW	✔	✔	✔	✗	NPV	✔	✔	✔	✗	Graphs illustrates electricity savings and LCC savings separately	Detailed analysis of 12 prototypical buildings that included 576 simulations to test improvement strategies Considers the time value of money	Results not integrated; The use of process data Does not provide a framework, method or tool that can help integrate LCA and LCC
Langston and Langston (2008), Australia	Reliability of embodied energy **modelling**	LCEA	IOH	?	✔	?	?	?	?	✔	?	?	?	Graph with embodied energy (GJ) on the Y-Axis and capital coast on the X-Axis.	The use of Input Output hybrid data Australian residential example	Results focus on capital cost instead of life cycle cost; Results focus on embodied energy instead of life cycle energy; Unclear if any other life cycle stages were considered; Does not provide a framework, method or tool that can help integrate LCA and LCC

Source	Title	LCA							LCC					Output	Strengths	Weaknesses
		LCEA/ LCGHGE	LCI Method	OE inclu-sions	System boundary				Method	System boundary						
					IEE	REE	OE	Demo		Initial	Oper.	Main.	Demo			
Leckner and Zmeureanu (2011), Canada	Life cycle cost and energy **analysis** of a net zero energy house with solar combi-system	LCEA	?	?	✔	✗	✔	✗	NPV and PP	✔	✔	✔	✗	LCC and LCEA results provided separately in graphs	Included analysis of passive design strategies first then followed by active building strategies Sensitivity analysis included variations to price of electricity and interest rates	Not a framework, method or tool for integrating LCA and LCC but merely an analysis using both methods separately; Results not integrated; Energy used for maintenance and dismantling of solar system not considered LCI data source and general formulas for LCA and LCC not provided
Menzies (2010), UK	Carbon, energy and monetary investment **model** for low carbon building design	LCEA & LCGHGE	P	?	✔	?	✔	?	NPV and PP	✔	✔	✔	✔	Tables. Information for energy, carbon and cost provided separately	Both energy and GHG analysed	Results not integrated; Does not really propose a model that integrates them. The term 'model' is misleading; Data inputs unclear Process data

Source	Title	LCA							LCC					Output	Strengths	Weaknesses
		LCEA/ LCGHGE	LCI Method	OE inclu-sions	System boundary				Method	System boundary						
					IEE	REE	OE	Demo		Initial	Oper.	Main.	Demo			
Mithraratne et al. (2007) and Vale and Mithraratne (2007), New Zealand	Life cycle analysis **model**	LCEA & LCGHGE	P	C H L A DHW	✔	✔	✔	?	?	✔	✔	?	?	Not provided	Applied to a residential case study User interface a series of forms requesting simple building information that is easily understood by designers	Unclear if maintenance and replacement energy and costs were considered; Data sources not provided; New Zealand specific data; Process data Does not provide a framework, method or tool that can help integrate LCA and LCC
Petrillo et al. (2016), Italy	**Tool** for the systematic sustainability assessment based on LCA and LCC	LCGHGE	?	C H	✔	✗	✔	✗	?	✔	✔	✔	✗	No output provided.	Detailed framework diagram; Include multi-criteria analysis Includes social indicators	REE not considered; Method very complex; Applicable to energy systems, not buildings Weighting method not provided for matrix results

Source	Title	LCA							LCC					Output	Strengths	Weaknesses
		LCEA/ LCGHGE	LCI Method	OE inclu-sions	System boundary				Method	System boundary						
					IEE	REE	OE	Demo		Initial	Oper.	Main.	Demo			
Ristimäki et al. (2013), Finland	**Framework** for LCC and LCA for an analysis of a new residential district energy system	LCGHGE	IO	C H L A DHW	✔	✔	✔	✗	NPV	✔	✔	✔	✗	Graph with NPV and GHG emissions on left and right axis	Results integrated. Time value for money considered	Truncation error due to IO data.; Equations and data inputs not provided Not applied to a whole building scale ; Finnish context Scaling factor for getting NPV and GHG on the same graph not provided
Savino et al. (2017), Italy	A new **model** for environmental and economic evaluation of renewable energy systems: The case of wind turbines	LCGHGE	P	?	✔	✔	✔	✔	NPV & PP	✔	✔	✗	✗	Colour coded matrix (divided between optimal to intolerable region) with payback on x-axis and $kgCO_2e$ on y-axis.	Results integrated; Includes demolition Includes 'optimal' solutions that have a low carbon footprint and low cost	Upstream impacts excluded due to process data; Weighting method not provided for matrix results

Source	Title	LCA							LCC					Output	Strengths	Weaknesses
		LCEA/ LCGHGE	LCI Method	OE inclu-sions	System boundary				Method	System boundary						
					IEE	REE	OE	Demo		Initial	Oper.	Main.	Demo			
Schwartz et al. (2016); UK	Implementing multi objective genetic algorithm for life cycle carbon footprint an life cycle cost minimisation: A building refurbishment case study	LCGHGE	P	C H L DHW	✔	✔	✔	✔	NPV	✔	✔	✔	✔	Graphs with life cycle carbon footprint on the X-axis and LCC of the Y-axis. Additional graphs illustrating embodied carbon and cost.	Results integrated and detailed graphs; Focus on refurbishment ; Most data inputs are clearly stated: LCI data source; Lifespan; wastage rate; cost of energy, heating system etc. Calculations provided	Time value of money not considered (no discount rate and inflation rate applied); The use of process data Does not provide a framework, method or tool that can help integrate LCA and LCC

Source	**Title**	**LCA**							**LCC**					**Output**	**Strengths**	**Weaknesses**
		LCEA/ LCGHGE	LCI Method	OE inclu-sions	System boundary				Method	System boundary						
					IEE	REE	OE	Demo		Initial	Oper.	Main.	Demo			
Stephan and Stephan (2016); Lebanon	Life cycle energy and cost analysis of embodied, operational and user-transport energy reduction measures for residential buildings	LCEA	IOH	C H L DHW	✔	✔	✔	✗	NPV	✔	✔	✔	✗	Bar graph providing LCEA and LCC of the proposed energy reduction measures over 50 years	Data inputs and calculations clearly stated ; Use of input-output based hybrid data ; Time value of money taken into account Sensitivity analysis testing the impact of alternative discount and inflation rates and primary energy conversion factor, for example.	The use of Australia LCI data for a Lebanese case study (thus data not context specific) Results valid for the base case study only

Review of life cycle analysis and life cycle cost commercial tools

Table A.2 Review of life cycle analysis and life cycle cost commercial tools

Tool Name, Author, year, country of origin	Detail	Strengths	Weaknesses
ENVEST 2 BRE Group (2016a), UK	• Web based tool. • Allows for the comparison of different building projects. • Originally an LCA tool that now includes LCC. • Concentrates on the key elements that contribute to most of the buildings environmental impacts. • Measures the environmental impact in terms of Ecopoints (dividing the impacts of UK by its population) • Two versions: Envest 2 estimator: cost and replacement intervals can not be changed by the user; Envest 2 calculator: user has the choice of entering their own information or using defaults	• Simplifies the analysis by only concentrating on the key building elements • Simple building data that is available at early stage design: form, materials, components, operating systems (Vijayan and Kumar, 2005) • Web based • Embodied element breakdown and pie charts (Vijayan and Kumar, 2005)	• Assigns 'Ecopoints- this weighting needs to be further explained as to how it is applied. • UK based • Embodied data source not clear • LCC formulas not transparent • Very basic and still requires investment and further development to make it fast and practical (Davies, 2007) • More detailed graphs needed • User parameters required • Truncation error due to process LCI data
SimaPro SimaPro (2016), The Netherlands	• A popular software tool within the LCA community (Fouche and Crawford, 2015) • Uses the Swiss based Ecoinvent (Wernet et al., 2016) database • Allows you to model products and systems • Includes uncertainty analysis • Pay subscription	• Industry recognised tool (myEcoCost, 2010) • Includes a significant amount of data • Exports data to Excel • Includes uncertainty analysis	• Time value of money not considered (Zuo et al., 2017) • No default cost entries. • Cost data can be difficult to gather. • Lack of transparency especially with regards to formulas and data sources (Heijungs et al., 2013). • Lack of documentation (Heijungs et al., 2013). • Takes a significant amount of time to use and master (Han, 2011) • Truncation error due to process LCI data

Tool Name, **Author, year, country of origin**	**Detail**	**Strengths**	**Weaknesses**
eTool eTool (2015), Australia	• An Australian LCA tool developed in Perth in 2009 • Can conduct LCC with the help of using IMPACT (as described below) • Web based • Produces reports in line with ISO 14044 and EN 15978 • Free version available but paid subscription required for consultant or specialist tool version.	• Allows costs to be assigned to materials, transport and services (Zuo et al., 2017). • Incorporates templates of common building materials which contain default quantities that are linked to LCI data. • Good for early design stage (Zuo et al., 2017). • Graphical outputs includes bar charts (which indicate how much the embodied and operational GHG impact is for the project). • Provides comparison of different project scenarios • Interface simple and easy to use (myEcoCost, 2010)	• Upstream environmental impacts excluded de to the use of cradle to factory gate process LCI data • Possible subjective weighting for environmental and economic score. Weighting methodology needs to be more transparent. • LCC formula and method used not provided • Limited research and critical review of tool. • Not suitable for the analysis of products or services (myEcoCost) • Currently only one data source
IMPACT BRE Group (2016b), UK	• Integrated material profile and costing tool • Database of cost and environmental data designed to be integrated into existing CAD/BIM programs such as IES and eTool • IMPACT compliant tools work by allowing the user to attribute environmental and cost information to drawn or scheduled items in the BIM. Put simply, IMPACT takes quantity information from the BIM and multiplies this by environmental impact and/or cost 'rates' to produce an overall impact and cost for the whole (or a selected part) of the design.	• Allows for the integration of sustainability certification assessments such as LEED and BREAAM that requires an LCA to be performed as part of a credit score. • Includes an environmental benchmarking that can compare project against a 'typical/average' project of the same nature.	• Building services not included in the scope of IMPACT (BRE Group, 2016b) • Time value of money consideration (such as discounting and inflation rate) not clear. • Formulas and database not transparent • Requires the user to have access and familiarity to compliant software programs such as IES or eTool.
TALLY KT Innovations et al. (2016), USA	• Add on to Revit software. Quantities generated by Revit are translated into areas and volumes that are appropriate for a custom-designed LCI database. • Allows architects and engineers to quantify the environmental impact of building materials for whole building analysis as well as comparative analyses of design options.	• Compatibility with popular industry tool Revit • Provides graphical output such as pie charts illustrating the global warming potential of key building elements and detailed bar charts breaking down the GHG performance per life cycle stage.	• Does not cover impacts from construction or operation (Zuo et al., 2017). • For USA based on 2013 data (Zuo et al., 2017). • Requires the user to have access and familiarity to compliant software programs such as Revit.

Tool Name, **Author, year, country of origin**	**Detail**	**Strengths**	**Weaknesses**
	• Uses a custom designed database in partnership with Thinkstep (2015)		
GABi Thinkstep (2015), Germany	• Can select multiple databases such as Ecoinvent or U.S. LCI • Web based platform that allows the user to track, manage and optimise every step of the supply chain for their project • Allows the creating of models based on physical process chains (engineering approach) (Calcas, 2008).	• Intuitive user interface; flexible inputs and outputs (Michalski, 2015) (Wilkinson, 2012) • Large amount of data: 8400 LCI databases (Thinkstep, 2015) • Widely used by LCA practitioners (Calcas, 2008) • Extension plug ins generate reports. • Own weighting patterns can be added by the user.	• Lack of transparency especially with regards to formula (Heijungs et al., 2013) (myEcoCost, 2010). • Lack of documentation (Heijungs et al., 2013) (myEcoCost, 2010). • Time consuming and intricate to use (Michalski, 2015) • Users have to manually insert costs (Calcas, 2008) • Process data used • Software clunky and requires a steep learning curve (myEcoCost, 2010)
BEES NIST (2010), USA	• The Building for Environmental and economic sustainability (BEES) • Can measure economic performance and environmental impact • Includes 230 building products • Compliant with ISO 14040 • All stages of the life cycle product are examined from raw material extraction to recycling and waste management • LCC is measures using the ASTM (American Society of Testing and Materials) standard LCC method and covers costs from initial to disposal. • Environmental and economic performance is combined into an overall performance measure using the ASTM standard for Multi-Attribute Decision Analysis.	• Can be applicable to any building stage (Michalski, 2015) • Significant amount of data provided • Includes all stages of the building life cycle • Graphical output includes bar graphs illustrating overall performance, economic and environmental performance	• Lack of transparency esp. with regards to formula (Heijungs et al., 2013). • Lack of documentation (Heijungs et al., 2013). • Process data used • Lacks transparency, formulas and information poorly labelled (BuildingGreen, 2000) • Impossible to explore upstream impacts (BuildingGreen, 2000). • Source of some data not clear and questionable (BuildingGreen, 2000).
OpenLCA	• LCC recently added to version 1.5 (2016) • Costs are modelled as properties	• Inputs can be modified by the user • Different currencies included	• Costs have to be entered manually • All inputs can be modified by the user which

Tool Name, **Author, year, country of origin**	**Detail**	**Strengths**	**Weaknesses**
GreenDelta (2016) Germany	• Costs can be positive or negative • Flow based approach to calculating LCC • Uses GaBi and Ecoinvent databases	• Includes uncertainty analysis • Export results to Excel • Open source, free, transparent • Open source software that is free of charge.	allows for a significant degree of subjectivity • LCC feature is new and more research into its reliability required • Lack of bulk edit function (such as changing the electricity mix for multiple processes in one step) (myEcoCost) • Process data used

Previous multi-criteria decision-making studies

Table A.3 Review of previous MCDM environmental related studies

Author	Detail	Key points
Buchert et al. (2015)	MCDM as a tool for sustainable product development	• Applicable to LCA due to large amount of data and multiple criteria involved with LCA • Applicability and necessity to early stage design process. • Applicability and usability to quantitative analysis • Cannot find one unique solution that optimises all objectives. Instead one has to deal with the trade-offs. • Use of indirect weighting according to the preferences of the user • Process specified: 1. Define research target/ objective 2. Define design parameters 3. Define life cycle stage to be included 4. Define alternatives 5. Define indicators/ criteria for evaluation to be based upon 6. Define data 7. Define assumption • Disadvantages/ Issues: o One of the main problems of mathematical trade-off analysis via decision trees is the definition of the regarded scope o More complex products require additional effort in modelling. o Level of detail is objective o Selection of indicators o Qualitative indicators are neglected o Acquisition of data
Pohekar and Ramachandran (2004)	MCDM for sustainable energy planning	• MCDM is gaining popularity and applicability to the energy/ environmental field • Provided a review of over 90 published papers • AHP most popular method followed by outranking techniques such as PROMETHEE and ELECTRE • Defined the MCDM process as: 1. Formulation of options and selection of criteria 2. Selection of decision process 3. Performance evaluation 4. Decide decision parameters 5. Application of the method 6. Evaluation of result 7. Decision

Author	Detail	Key points
Wang et al. (2009)	MCDM for sustainable energy decision making	• Applicability to sustainable decision making • Popularity of cost and CO_2 as being some of the main criteria included in MCDM problems • Provides an example of the framework process • Suitable for problems with high uncertainty, conflicting objectives, different forms of data, multi-interests and perspectives • MCDM usually includes four main stages: 1. Alternatives formulation and criteria selection 2. Criteria weighting 3. Evaluation 4. Final treatment • Prelim step: Formulate the alternatives • Provides good breakdown of the typical criteria looked at for economic and environmental studies • AHP is widely used and applicable to energy systems studies • AHP is a type of weighted sum method • Provides a good breakdown all the methods. • Disadvantages/ Issues: o Need to select appropriate methods, aggregation and weighting o Needs to be suitable to the specific design problem
Ananda and Herath (2009)	MCDM with forest management	• AHP one of the more common techniques along with Multi-attribute value theory (MAVT), multi-attribute utility theory (MAUT)
Kiker et al. (2005)	MCDM for environmental decision making	• MCDM applicable to a wide range of environmental criteria, not just monetary criteria • AHP, MAVT and MAUT are optimisation methods. They employ numerical scores to communicate the merit of one option in comparison to others. • Suggests the use of ranking and weighting in the decision process (such as AHP) • Environmental decision-making also involves complex trade offs between divergent criteria. • Disadvantages/Issues: o No mandatory legislation to follow but several guidance documents exist. o Need to correct combination of people in the decision process o Each MCDM method has strengths and limitations
Diakaki and Grigoroudis (2008)	MCDM for improving energy efficiency in buildings	• MCDM is an appropriate tool in which to explore the trade offs between energy efficiency solutions. • MCDM often used in combinations with simulation. Where simulation results are evaluated with other criteria such as capital cost • Proposes the use and development of the multi-objective approach. • Proposes the use of a decision model • Also looked at glazing and insulation. • Looked at the relationship between operational energy and capital cost

Author	Detail	Key points
		• Disadvantages/ Issues: o No optimal solution exists when it comes to energy efficiency solutions due the amount of complex and competitive criteria o Outcome severally influenced by the knowledge of the decision maker o Only considered capital cost and operational energy o Fails to take into account 'real world dimensions' such as time and user behaviour changes etc.
Zhang et al. (2014)	MCDM framework for the selection of low carbon building measures for office building in Hong Kong	• Integration of economic and environmental criteria for MCDM works for low carbon assessment • Developed a selection criteria framework for the selection of low carbon building measures. • They applied weighting in % terms with payback criterion having the highest weighing (52%) and then initial cost (21%) followed by technical reliability (12%) • Disadvantages/ Issues: o Only considered operational energy and capital cost o Weighting can be very subjective
Greening and Bernow (2004)	MCDM in energy and environmental policies	• Use of MCDM in an integrated assessment (IA) provides an ideal framework to assess multiple environmental criteria and especially cost/benefit criteria • IA good at identifying the trade-offs between criteria
Kumar et al. (2017)	MCDM in sustainable renewable energy development	• Utility based models are preferred for ranking energy and technologies of which AHP is the most popular. • AHP is adaptable and easy to use. Each criterion can be transparent. • AHP applicable to energy decisions. • AHP can handle both quantitative and qualitative criteria • Steps to AHP: 1. Defining objective into a hierarchical problem 2. Determining weights for each criteria 3. Calculating score of each alternative considering criteria 4. Calculating overall score of each alternative • Other possible methods: ELECTRE (less versatile); TOPSIS (Doesn't consider any difference between positive and negative values), VIKOR (complex to model over time). • Disadvantages/ Issues: o Interdependency between objectives and alternatives leads to hazardous results. o Involvement of more decision maker can make the problem more complicated while assigning weights. o Demands data collected based on experience
Haralambopoulos and	Structuring a MCDM	• Example of the development of an "integrated dynamic" framework using MCDM • Framework has an iterative structure

Author	Detail	Key points
Polatidis (2003)	framework for renewable energy projects	• Includes sensitivity analysis • Includes weighting • Includes the following criteria: energy saved; return on investment and number of jobs created • Uses an impact scale 1-10 • Outranking methods are generally assumed to be well suited for energy and environmental planning issues. • Use the PROMETHEE II method
Zavadskas and Turskis (2011)	MCDM in economics	• The philosophy of decision making in economics is to assess and select the most preferable solution, implement it and to gain the biggest profit. • MCDM is beneficial to economic analysis and presents a large number of studies that have used MCDM in for economic evaluations. • Disadvantages/ Issues: o Need to develop different scaling methods o Develop new mathematical models to solve outranking problems
Zopounidis and Doumpos (2002)	MCDM in financial decision making	• MCDM is well suited for financial decision-making problems • Application of MCDM in financial decisions: bankruptcy and credit risk assessment; portfolio selection; investment appraisal • AHP has been used for investment appraisal • MCDM contributes in a very original way to the investment decision process, supporting all stages of the investment process. • MCDM can contribute through identification of the nest investment projects according to the problematic chosen and is good at revealing the investors preferences and system of values • Allows the DM to participate on the problem • MCDM methods seem to have a promising future in the field of financial management, because they offer a highly methodological and realistic framework to decision problems. • Disadvantages/ Issues: o The ‘optimal’ decision is not really optimal in the traditional optimization perspective. o The aggregation method o Success of outcome relies on the computer program selected

Appendix B: Predefined input parameters

Global warming potential and emission factors

Table B.1 Global warming potential and emission factor for various GHGE

Fuel	GHG	Emission factor (kg/GJ)	Global warming potential (CO_2e)
Electricity (Brown Coal)	Carbon dioxide (CO_2)	92.7	1
	Methane (CH_4)	0.00048	25
	Nitrous oxide (N_2O)	0.0013	298
Gas	Carbon dioxide (CO_2)	51.2	1
	Methane (CH_4)	0.0048	25
	Nitrous oxide (N_2O)	0.000097	298

Source: Crawford, (2011)

Primary energy conversion factor

Table B.2 Primary energy conversion factor

Fuel	Primary energy factor
Natural gas	1.4
Electricity	3.4

Source: Treloar (1998)

Constraint factor

The constraint factors recommended are 0.45 and 0.4 for the heating and cooling energy for Victorian dwellings, respectively (AGO, 1999; Fuller and Crawford, 2011).

Replacement rates of materials

Table B.3 Average material replacement rate values

Material	Average replacement rate (years)	Source
Concrete roof tiles	40	Ransley and Tyrrell (1998), Condor (2008)
Bricks	Lifetime	Seiders et al. (2007);Chapman and Izzo (2002)
Plasterboard	35	Ransley and Tyrrell (1998)
Water-based paint	10	InterNACHI (2012); Fay et al. (2000)
Aluminium-framed windows	25	LCCS (2001); Condor (2008); Thomas et al. (2015)
Timber-framed windows	40	(Ransley and Tyrrell, 1998); InterNACHI (2012); Seiders et al. (2007)
Nylon carpet	25	Bowyer (2009); Condor (2008)

Total energy requirement of building sector

For the Australian residential building sector this value is 10.633 GJ/AUD1000 and for the commercial building sector it is 9.979 GJ/AUD1000, based on 1996-1997 (the latest available) energy based input-output data for Australia (Crawford, 2011).

Material wastage coefficients

Table B.4 Wastage factors

Material	Wastage factor (%)	Material	Wastage factor (%)
Concrete	115	Steel	105
Glass	103	Insulation	110
Paint	105	Timber	105

Source: Crawford (2004)

Material embodied energy coefficients

Table B.5 Material embodied energy coefficients

Material	Unit	Embodied energy coefficient (GJ/unit)
Aluminium		
Virgin	t	252.6
Reflective foil	m^2	0.137
Carpet	m^3	3.08
Wool	m^2	0.741
Nylon	m^2	0.683
Ceramics		
Clay brick (110mm)	m^2	0.56
Ceramic tiles	m^2	0.29
Concrete		
15 MPa	m^3	4.03
20 MPa	m^3	4.44
30 MPa	m^3	5.44
40 MPa	m^3	6.75
Cement	t	16.96
Concrete roof tiles	m^2	0.251
Glass		
Clear float (4mm)	m^2	1.73
Toughened glass (6mm)	m^2	3.66
Double glazing	m^2	3.46
Triple glazing	m^2	5.19
Insulation		
EPS R2	m^3	7.22
Fibreglass insulation R2	m^3	2
Straw	m^3	1.29
Paint		
Oil-based paint	m^2	0.101
Water-based paint	m^2	0.096
Plasterboard		
10mm	m^2	0.207
13mm	m^2	0.232
Plastics		
General (PVC)	t	156.9
Polyester	t	156.9
Polystyrene	m^3	7.04
Sand and stone		
Granite	t	0.087
Sand	m^3	0.617
Steel		
Stainless steel	t	445.2
Steel	t	85.46
Timber		

Hardwood	m^3	21.33
Softwood	m^3	10.93

Source: Crawford (2011)

Building cost index

Table B.6 Building cost index

Building cost index year	Value
1997	99.3
2017	196.2

Source: Rawlinsons (2017)

Total energy requirement of materials

The values in the tables below are based on the energy intensities (EI) provided in Crawford (2011), Crawford and Treloar (2010) and Treloar and Crawford (2004) and are based on pure IO data.

Table B.7 Total energy requirement of materials

Total EI (GJ/AUD 1000)	Stage 1	Total EI (GJ/AUD 1000)	Stage 1
1.1985	Ceramic products	0.0146	Other agriculture
0.9900	Cement, lime and concrete slurry	0.0110	Rail, pipeline and other transport
0.3757	Road transport	0.0481	Other business services
0.4538	Iron and steel	0.1259	Paints
0.3847	Other non-metallic mineral products	0.0171	Retail trade
0.3509	Wholesale trade	0.0611	Legal, accounting, marketing and business management services
1.1090	Residential building	0.0225	Communication services
0.7277	Other wood products	0.0117	Other construction
0.1026	Other mining	0.1166	Other electrical equipment
0.3546	Sawmill products	0.0725	Agricultural, mining and construction machinery
0.4062	Plaster and other concrete products	0.0288	Other chemical products
0.8764	Structural metal products	0.0361	Motor vehicles and parts; other transport equipment
0.3150	Fabricated metal products	0.0832	Other machinery and equipment
0.0511	Textile products	0.0471	Mechanical repairs
0.0282	Basic non-ferrous metal and products	0.0172	Other repairs
0.0174	Air and space transport	0.0182	Scientific research, technical and computer services
0.0254	Glass and glass products	0.0106	Publishing; recorded media and publishing
0.0112	Basic chemicals	0.0298	Electronic equipment
0.3548	Other property services	0.0112	Government administration

Total EI (GJ/AUD 1000)	Stage 1	Total EI (GJ/AUD 1000)	Stage 1
0.5780	Household appliances	0.0230	Printing and services to printing
0.0647	Accommodation, cafes and restaurants	0.0150	Prefabricated buildings
0.1238	Sheet metal products	0.0125	Water supply; sewerage and drainage services
0.2055	Plastic products	0.0300	Furniture
0.0113	Insurance	0.0286	Banking
0.0192	Non-bank finance		

Total energy requirement of material being not being replaced

The values in the tables below are based on the energy intensities (EI) provided in Crawford (2011), Crawford and Treloar (2010) and Treloar and Crawford (2004)and are based on pure IO data. This is a list of total energy requirements IO pathways for materials not replaced at the time of main material replacement and therefore subtracted from embodied GHGE calculation.

Table B.8 Total energy requirement of material not being replaced: Paint, textile and ceramic

Main material being replaced					
Paint		Textile		Ceramic	
Total EI (GJ/AUD1000)	Stage 1	Total EI (GJ/AUD 1000)	Stage 1	Total EI (GJ/AUD 1000)	Stage 1
1.1985	Ceramic products	1.1985	Ceramic products	0.9900	Cement, lime and concrete slurry
0.9900	Cement, lime and concrete slurry	0.9900	Cement, lime and concrete slurry	0.4538	Iron and steel
0.4538	Iron and steel	0.4538	Iron and steel	0.3847	Other non-metallic mineral products
0.3847	Other non-metallic mineral products	0.3847	Other non-metallic mineral products	0.7277	Other wood products
0.7277	Other wood products	0.7277	Other wood products	0.1026	Other mining
0.1026	Other mining	0.1026	Other mining	0.3546	Sawmill products
0.3546	Sawmill products	0.3546	Sawmill products	0.4062	Plaster and other concrete products
0.4062	Plaster and other concrete products	0.4062	Plaster and other concrete products	0.8764	Structural metal products
0.8764	Structural metal products	0.8764	Structural metal products	0.3150	Fabricated metal products
0.3150	Fabricated metal products	0.3150	Fabricated metal products	0.0511	Textile products
0.0511	Textile products	0.0282	Basic non-ferrous metal and products	0.0282	Basic non-ferrous metal and products
0.0282	Basic non-ferrous metal and products	0.0254	Glass and glass products	0.0254	Glass and glass products
0.0254	Glass and glass products	0.0112	Basic chemicals	0.0112	Basic chemicals
0.0112	Basic chemicals	0.5780	Household appliances	0.5780	Household appliances
0.1238	Sheet metal products	0.1238	Sheet metal products	0.1238	Sheet metal products

Main material being replaced					
Paint		Textile		Ceramic	
0.2055	Plastic products	0.2055	Plastic products	0.2055	Plastic products
0.0146	Other agriculture	0.0146	Other agriculture	0.0146	Other agriculture
0.0117	Other construction	0.0110	Rail, pipeline and other transport	0.1259	Paints
0.1166	Other electrical equipment	0.1259	Paints	0.1166	Other electrical equipment
0.0725	Agricultural, mining and construction machinery	0.0117	Other construction	0.0725	Agricultural, mining and construction machinery
0.0288	Other chemical products	0.1166	Other electrical equipment	0.0288	Other chemical products
0.0361	Motor vehicles and parts; other transport equipment	0.0725	Agricultural, mining and construction machinery	0.0361	Motor vehicles and parts; other transport equipment
0.0832	Other machinery and equipment	0.0288	Other chemical products	0.0832	Other machinery and equipment
0.0471	Mechanical repairs	0.0361	Motor vehicles and parts; other transport equipment	0.0471	Mechanical repairs
0.0298	Electronic equipment	0.0832	Other machinery and equipment	0.0298	Electronic equipment
0.0150	Prefabricated buildings	0.0471	Mechanical repairs	0.0150	Prefabricated buildings
0.0125	Water supply; sewerage and drainage services	0.0298	Electronic equipment	0.0125	Water supply; sewerage and drainage services
0.0300	Furniture	0.0150	Prefabricated buildings	0.0300	Furniture
		0.0125	Water supply; sewerage and drainage services		
		0.0300	Furniture		
6.7526	**Total**	**7.4164**	**Total**	**6.2463**	**Total**

Table B.9 Total energy requirement of material not being replaced: Wood, steel and glass

Wood		Steel		Glass	
Total EI (GJ/AUD1000)	**Stage 1**	**Total EI (GJ/AUD 1000)**	**Stage 1**	**Total EI (GJ/AUD 1000)**	**Stage 1**
1.1985	Ceramic products	1.1985	Ceramic products	1.1985	Ceramic products
0.9900	Cement, lime and concrete slurry	0.9900	Cement, lime and concrete slurry	0.9900	Cement, lime and concrete slurry
0.4538	Iron and steel	0.3847	Other non-metallic mineral products	0.4538	Iron and steel
0.3847	Other non-metallic mineral products	0.7277	Other wood products	0.3847	Other non-metallic mineral products
0.1026	Other mining	0.1026	Other mining	0.7277	Other wood products
0.4062	Plaster and other concrete products	0.3546	Sawmill products	0.1026	Other mining
0.8764	Structural metal products	0.4062	Plaster and other concrete products	0.3546	Sawmill products
0.3150	Fabricated metal	0.0511	Textile products	0.4062	Plaster and other concrete

Wood		Steel		Glass	
	products				products
0.0511	Textile products	0.0282	Basic non-ferrous metal and products	0.8764	Structural metal products
0.0282	Basic non-ferrous metal and products	0.0254	Glass and glass products	0.3150	Fabricated metal products
0.0254	Glass and glass products	0.0112	Basic chemicals	0.0511	Textile products
0.0112	Basic chemicals	0.5780	Household appliances	0.0282	Basic non-ferrous metal and products
0.5780	Household appliances	0.2055	Plastic products	0.0112	Basic chemicals
0.1238	Sheet metal products	0.0146	Other agriculture	0.5780	Household appliances
0.2055	Plastic products	0.1259	Paints	0.1238	Sheet metal products
0.0146	Other agriculture	0.0117	Other construction	0.2055	Plastic products
0.1259	Paints	0.1166	Other electrical equipment	0.0146	Other agriculture
0.0117	Other construction	0.0725	Agricultural, mining and construction machinery	0.1259	Paints
0.1166	Other electrical equipment	0.0288	Other chemical products	0.0117	Other construction
0.0725	Agricultural, mining and construction machinery	0.0361	Motor vehicles and parts; other transport equipment	0.1166	Other electrical equipment
0.0288	Other chemical products	0.0832	Other machinery and equipment	0.0725	Agricultural, mining and construction machinery
0.0361	Motor vehicles and parts; other transport equipment	0.0471	Mechanical repairs	0.0288	Other chemical products
0.0832	Other machinery and equipment	0.0298	Electronic equipment	0.0361	Motor vehicles and parts; other transport equipment
0.0471	Mechanical repairs	0.0150	Prefabricated buildings	0.0832	Other machinery and equipment
0.0298	Electronic equipment	0.0125	Water supply; sewerage and drainage services	0.0471	Mechanical repairs
0.0150	Prefabricated buildings	0.0300	Furniture	0.0298	Electronic equipment
0.0125	Water supply; sewerage and drainage services			0.0150	Prefabricated buildings
0.0300	Furniture			0.0125	Water supply; sewerage and drainage services
				0.0300	Furniture
6.3742	**Total**	**5.6875**	**Total**	**7.4312**	**Total**

Table B.10 Total energy requirement of material not being replaced: Concrete, plastic and plasterboard

Concrete		Plastic		Plasterboard	
Total EI (GJ/AUD1000)	**Stage 1**	**Total EI (GJ/AUD 1000)**	**Stage 1**	**Total EI (GJ/AUD 1000)**	**Stage 1**
1.1985	Ceramic products	1.1985	Ceramic products	1.1985	Ceramic products
0.4538	Iron and steel	0.9900	Cement, lime and concrete slurry	0.9900	Cement, lime and concrete slurry
0.3847	Other non-metallic mineral products	0.4538	Iron and steel	0.4538	Iron and steel
0.7277	Other wood products	0.3847	Other non-metallic mineral products	0.3847	Other non-metallic mineral products
0.1026	Other mining	0.7277	Other wood products	0.1026	Other mining
0.3546	Sawmill products	0.1026	Other mining	0.3546	Sawmill products
0.8764	Structural metal products	0.3546	Sawmill products	0.4062	Plaster and other concrete products
0.3150	Fabricated metal products	0.4062	Plaster and other concrete products	0.8764	Structural metal products
0.0511	Textile products	0.8764	Structural metal products	0.3150	Fabricated metal products
0.0282	Basic non-ferrous metal and products	0.3150	Fabricated metal products	0.0511	Textile products
0.0254	Glass and glass products	0.0511	Textile products	0.0282	Basic non-ferrous metal and products
0.0112	Basic chemicals	0.0282	Basic non-ferrous metal and products	0.0254	Glass and glass products
0.5780	Household appliances	0.0254	Glass and glass products	0.0112	Basic chemicals
0.1238	Sheet metal products	0.0112	Basic chemicals	0.5780	Household appliances
0.2055	Plastic products	0.5780	Household appliances	0.1238	Sheet metal products
0.0146	Other agriculture	0.1238	Sheet metal products	0.2055	Plastic products
0.1259	Paints	0.0146	Other agriculture	0.0146	Other agriculture
0.0117	Other construction	0.1259	Paints	0.1259	Paints
0.1166	Other electrical equipment	0.0117	Other construction	0.0117	Other construction
0.0725	Agricultural, mining and construction machinery	0.1166	Other electrical equipment	0.1166	Other electrical equipment
0.0288	Other chemical products	0.0725	Agricultural, mining and construction machinery	0.0725	Agricultural, mining and construction machinery
0.0361	Motor vehicles and parts; other transport equipment	0.0288	Other chemical products	0.0288	Other chemical products
0.0832	Other machinery and equipment	0.0361	Motor vehicles and parts; other transport equipment	0.0361	Motor vehicles and parts; other transport equipment
0.0471	Mechanical repairs	0.0832	Other machinery and equipment	0.0832	Other machinery and equipment
0.0298	Electronic equipment	0.0471	Mechanical repairs	0.0471	Mechanical repairs
0.0150	Prefabricated buildings	0.0298	Electronic equipment	0.0298	Electronic equipment

	Concrete		Plastic		Plasterboard
0.0125	Water supply; sewerage and drainage services	0.0150	Prefabricated buildings	0.0150	Prefabricated buildings
0.0300	Furniture	0.0125	Water supply; sewerage and drainage services	0.0125	Water supply; sewerage and drainage services
		0.0300	Furniture	0.0300	Furniture
6.0604	**Total**	**7.2510**	**Total**	**6.7288**	**Total**

Table B.11 Total energy requirement of material not being replaced: Aluminium

Aluminium			
Total EI (GJ/AUD1000)	**Stage 1**	**Total EI (GJ/AUD1000)**	**Stage 1**
1.1985	Ceramic products	0.1259	Paints
0.9900	Cement, lime and concrete slurry	0.0117	Other construction
0.4538	Iron and steel	0.1166	Other electrical equipment
0.3847	Other non-metallic mineral products	0.0725	Agricultural, mining and construction machinery
0.7277	Other wood products	0.0288	Other chemical products
0.1026	Other mining	0.0361	Motor vehicles and parts; other transport equipment
0.3546	Sawmill products	0.0832	Other machinery and equipment
0.4062	Plaster and other concrete products	0.0471	Mechanical repairs
0.8764	Structural metal products	0.0172	Other repairs
0.3150	Fabricated metal products	0.0298	Electronic equipment
0.0511	Textile products	0.0150	Prefabricated buildings
0.0254	Glass and glass products	0.0125	Water supply; sewerage and drainage services
0.0112	Basic chemicals	0.0300	Furniture
0.5780	Household appliances	0.2055	Plastic products
0.1238	Sheet metal products	0.0146	Other agriculture
7.4456	**Total**		

Appendix C: User defined input parameters

Bill of quantities

Table C.1 Bill of quantitates for case study building

Component	Material	Material Quantity	Material Quantity unit	Embodied energy coefficient (GJ/unit)[1]	Wastage multiplier[1]
Foundation, ground floor					
Ground floor	Concrete slab	48.00	m^3	4.44	1.1
	Polystyrene waffle pods	40.54	m^3	7.04	1.05
	Steel reinforcement Bar	0.34	t	85.46	1.05
	Steel reinforcement Mesh	0.37	t	85.46	1.05
	Plastic membrane	229.00	m^2	0.51	1.05
External wall					
External cladding	Clay brick	165	m^2	0.56	1.05
Wall ties	Stainless Steel	0.04280	t	85.46	1.05
Insulation	Aluminium Reflective foil	134	m^2	0.14	1.1
	R2 Fibreglass insulation	11	m^3	2	1.1
Internal lining	Plasterboard	150	m^2	0.21	1.05
Timber framing					
Framing	Softwood	8.48	m^3	10.9	1.02
Internal wall					
Finish	Plasterboard	775	m^2	0.21	1.05
	Insulation (garage wall)	2.33	m^3	2	1.1
Roof					
Tiles	Concrete	289.00	m^2	0.251	1.1
Insulation	Aluminium Reflective foil	289.00	m^2	0.14	1.1
Frame: Rafters & ridge beams	Softwood	2.99	m^3	10.9	1.02
Purlins/ Girders	Softwood	0.38	m^3	10.9	1.02
Insulation	Glasswool ceiling batts, R4	44.00	m^3	2	1.1
Finish	Plasterboard	226	m^2	0.21	1.05
Gutter	Steel	0.021	t	0.933	1.05
Windows					
Frame	Aluminium	0.15	t	252.6	1.1

Component	Material	Material Quantity	Material Quantity unit	Embodied energy coefficient (GJ/unit)[1]	Wastage multiplier[1]
Glass	Clear	30	m^2	1.73	1.03
Doors					
Panel	MDF	0.56	m^3	30.35	1.05
Frame	Hardwood	0.052	m^3	21.33	1.02
Internal finishes					
Floor	Nylon Carpet	137	m^2	0.68	1.05
	Ceramic tiles	35	m^2	0.293	1.05
Wall	Water-based paint	534.00	m^2	0.096	1.05
	Ceramic tiles	0	m^2	0.293	1.05
Ceiling	Water-based paint	226	m^2	0.096	1.05
Doors	Water-based paint	50	m^2	0.096	1.05

Source: 1 (Crawford, 2011)

Insulation scenarios

Table C.2 Glasswool insulation scenarios based on R-value

Insulation material	R value (m^2k/W)[1]	Thickness (mm)[1]	Density (kg/m^3)[1]	Thermal conductivity (W/mK)[3]	Embodied energy coefficient (GJ/m^2)[2]	Wastage factor (%)[2]	2017 Cost (AUD/m^2)[1]	Average material service life[4]
Walls								
Glasswool	R 2	90	11	0.045	0.18	1.1	9.29	Lifetime
	R3	100	32	0.032	0.58		22	
Ceiling								
Glasswool	R 4	195	11	0.045	0.39	1.1	13.07	Lifetime
	R 5	215	11	0.045	0.43		17.32	
	R 6	250	11	0.045	0.5		22.49	

Sources: [1] Fletcher Insulation (2016) [2] Crawford (2011) [3] CIBSE (2006) [4] Rauf and Crawford (2013) [5] (NAHB, 2007)

Table C.3 Embodied energy coefficients for insulation scenarios based on different densities

Insulation material	R value (m^2k/W)	Thickness (mm)	Density (kg/m^3)	Thermal conductivity (W/mK)[3]	Embodied energy coefficient (GJ/Unit)[2]	Wastage factor (%)[2]	2017 Cost (AUD/m^2)	MSL (Years)
Walls								
Glasswool	2	90	11	0.045	0.18 GJ/m^2 2 GJ/m^3	1.1	9.29[1]	Lifetime[4]
Expanded polystyrene (EPS)	2	70	16	0.036	0.51 GJ/m^2 7.22 GJ/m^3	1.1	17[7]	Lifetime[5]
Straw	2	140	240	0.07	0.18 GJ/m^2 1.29 GJ/m^3	1.1	21[8]	Lifetime[6]
Ceiling								
Glasswool	4	195	11	0.045	0.39 GJ/m^2 2 GJ/m^3	1.1	13.07[1]	Lifetime[4]
Expanded polystyrene (EPS)	4	150	16	0.036	1.08 GJ/m^2 7.22 GJ/m^3	1.1	20	Lifetime[5]
Straw	4	280	240	0.07	0.36 GJ/m^2 1.29 GJ/m^3	1.1	25	Lifetime[6]

Sources: [1] Fletcher Insulation (2016) [2] Crawford (2011) [3] CIBSE (2006) [4] NAHB (2007) [5] EUMEPS (2009) [6] Downton (2013) [7] Rawlinsons (2017) [8] Ausbale (2017).

Glazing scenarios

Table C.4 Glazing scenarios U-Values and service life

Type	U-Value (W/m^2K)	Average service life (years)
Single glazing, aluminium frame	6.9	25
Single glazing, timber frame	5.5	40
Double glazing, aluminium frame	3.5	25
Double glazing, timer frame	3	40
Triple glazing, aluminium frame	1.53	25
Triple glazing, timber frame	0.6	40

Sources: (Rauf and Crawford, 2013) (Asif et al., 2011) (U.S Department of Energy, 2016) 4 (Howard et al., 2007) (Chapman and Izzo, 2002)

Table C.5 Glazing scenarios: Environmental data

Glazing aspect	Type	Detail	Embodied energy coefficient (GJ/unit)[1]	Wastage factor (%) [1]
Pane material	Single glazing	4mm thick, clear	1.73 GJ/m^2 432.5 GJ/m^3	1.03
	Double glazing	4mm glass, 6mm air gap, 4 mm glass, clear	3.46 GJ/m^2 432.5 GJ/m^3	1.03
	Triple glazing	4mm glass, 6mm air gap, 4 mm glass, 6mm air gap, 4mm glass, clear	5.19 GJ/m^2 432.5 GJ/m^3	1.03
Frame material	Aluminium	Light, durable due to high strength to weight ratio; Low cost and maintenance requirements; High thermal conductivity High environmental impact (energy intensive to manufacture)	252.6 GJ/t	1.1
	Timber	Low environmental impact; Good thermal conductivity ; Requires more maintenance than aluminium and PVC because they are affected by weathering conditions; High cost	21.33 GJ/m^3	1.02

Source: 1 (Crawford, 2011)

Total energy requirement of residential case study building

Table C.6 Total energy requirement for the input-output sectors covering the residential building materials

Input-output pathway	Materials	Elements	TER *(GJ/A$1000)*
Basic non-ferrous metal and products	Aluminium reflective foil, aluminium, copper	Sisalation, tile trim, wardrobe and shower frames water pipes	0.0282
Basic chemicals	Polystyrene	Slab (waffle pods)	0.0112
Cement, lime and concrete slurry	25 MPa concrete, mortar	Slab, bricks walls	0.9900
Ceramic products	Clay bricks, ceramic tiles, ceramics	External walls, wall and floor finishes, toilet suite basin	1.1985

Input-output pathway	Materials	Elements	TER *(GJ/A$1000)*
Fabricated metal products	Steel	Fixings, bracing, bolts, washers, door handles, taps, garage door, sinks, hinges	0.3150
Glass and glass products	Toughened glass (6mm), clear float glass (4mm)	Shower screens, mirrors	0.0254
Iron and steel	Steel	Bracing	0.4538
Other mining	Screenings, sand	Slab base, brick walls	0.1026
Other non-metallic mineral products	Fibreglass insulation, various thicknesses	Wall and ceiling insulation	0.3847
Paints	Water based paint, oil-based paint	Wall, ceiling, door, jamb, architrave, reveal, eave, lintel, beam and batten finishes	0.1259
Plaster and other concrete products	Fibre cement sheet (4.5mm), plasterboard (10mm), concrete roof tile (20mm)	External wall infills, internal wall and ceiling cladding, cornice, roof cladding	0.4062
Plastic products	Plastic membrane (1mm), UPVC pipe 100, plastic	Slabs, drains, damp proof course, showers base, bath, water pipes, light points, power outlets, exhaust fans, light shade, wiring	0.2055
Sawmill products	Softwood, hardwood	Wall framing, roof framing, external joinery, battens	0.3546
Sheet metal products	Steel	Brick ties, bracing, roof valleys, fascia's, gutters, downpipes, flashings	0.1238
Structural metal products	Steel, windows (aluminium, clear flat glass, 4mm)	Slab reinforcement, lintels, aluminium, windows	0.8764
Textile products	Nylon carpet	Floor covering	0.0511
Total			5.6530

Assumptions

The following assumptions have been made in relation to the calculation of embodied energy and GHG emissions for the reference building.

Table C.7 Embodied energy and GHG emissions analysis assumptions

Assumption	Description
Replacement rate	Often materials are replaced sooner than predicted or are replaced with something completely different. As this is quite difficult to predict and is very dependant on user preferences, it has been assumed that as soon as a material reaches the end of its useful life the material will be replaced with the same material.
Future embodied energy values	While it is highly unlikely that embodied energy of materials will remain the same in the future as it is today, the embodied energy coefficient has been assumed to remain the same throughout the reference building's useful life. This is due to difficulty and uncertainty predicting future energy implications (such as factors affecting fuel mix; emission factor or advances in technology etc.)

Table below provides a list of the assumptions made in the calculation of the operational energy and GHG emissions for the reference building and PDS modifications analysed.

Table C.8 Operational energy and GHG emission calculation assumptions

Assumption	Description
Future energy consumption	Assumed that the energy consumption will remain the same over the expected lifetime of the building. This might be different in real life as building users and behaviour change over time.
Adjacent buildings	No adjacent buildings have been taken into account in the simulation process. The focus of the study is on the performance of an individual building and its components.
Landscaping and vegetation	Vegetation has been proven to impact the local microclimates by intercepting solar radiation and shading heat-absorbing structural materials (Wang et al., 2016). However the inclusion of this falls outside the scope of this study.
Building use	The use of the building is assumed to stay the same over the life span of the building.

Table below briefly describes the assumptions made in the calculating the LCC of the reference building.

Table C .9 Life cycle costing assumptions

Assumption	Description
End of life costs	This life cycle stage falls outside the scope of the study and has not been taken into account.
Future discount rate and inflation	It is assumed that the inflation rate and discount rate will stay the same throughout the period of analysis. This might not be the actual case, however due to difficulty and uncertainty towards estimating these future cost predictions, the value has remained the same for ease of calculation.
Cost of material	Based on Australian values, not international. Based on 2017 values as provided by (Rawlinsons, 2017)
Accuracy of exact values	The values used in this study are not meant to be exact. They provide merely a rough indication of what the possible values can be so as to demonstrate the key findings of this study. The values, for example, include the quantity of material; the cost of material and cost of fuel. There is a large degree of uncertainty and speculation involved with costing studies, thus a certain degree of flexibility should be accounted for.
Future energy consumption	Future energy consumption will be based on the same determinants used for the base case (i.e. energy needs will not change due to change to number of occupants and use of the building in the future). However, this is most likely not the case in reality as households energy demand can change yearly,. However, due to its unpredictable nature the long-term energy demand falls outside the scope of this study. The sensitivity of this assumption has been tested.
Labour	The price of labour is not included in this study
Fuel mix	Both gas and electricity is assumed to be used in the case study building. This however can differ from one dwelling to the next with other sources such as wood, LPG or renewable energy being used.