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Development of a sustainability approach for the structural design of buildings

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UNIVERSITY OF WOLLONGONG

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DEVELOPMENT OF A SUSTAINABILITY APPROACH FOR THE STRUCTURAL
DESIGN OF BUILDINGS

A thesis submitted in fulfilment of the
requirements for the award of the degree

DOCTOR OF PHILOSOPHY

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by

MEHDI ROBATI

SUSTAINABLE BUILDINGS RESEARCH CENTRE
FACULTY OF ENGINEERING AND INFORMATION SCIENCE

2017
In this path (of knowledge), you will not reach your goal without effort: Follow thy master (murshid), if you seek the reward.

Hafez (Ghazal 250), 14th century Persian poet
Declaration

I, Mehdi Robati, declare that this thesis submitted in fulfilment of the requirements for the conferral of the degree of Doctor of Philosophy from the University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. This document has not been submitted for qualifications at any other academic institution.

__________________________

Mehdi Robati

Jun 7th, 2017
Abstract

Sustainability in the building industry means ensuring that a building is ecologically friendly and economically feasible, as well as providing a healthy internal atmosphere for the occupants. Recent developments in low CO₂-e emissions design have highlighted the need to comprehend the characteristics and constraints of design alternatives at a global scale before making an appropriate choice. Despite the improvements in low CO₂-e emissions design, the guidance currently available to structural engineers on how to incorporate whole of life CO₂-e emissions impact in building design is still limited. This research seeks to identify the structural systems needed to sustain the long-term performance of a commercial building. To accomplish this goal, a typical 15 story office building in Australia was analysed to evaluate the potential impact of various forms of construction and structural concrete over the building’s lifetime. This particular building is one of four benchmark buildings proposed by the National Standard Development Organization. The effect of different types of concrete and structural flooring systems on its overall life cycle costs and carbon emissions (CO₂-e emissions) are quantified. This research adopted different life cycle assessment tools and databases to measure the energy consumed by this building from its construction to the day it no longer exists.

This research also assessed existing literature in the field of minimising the CO₂-e emissions impact of concrete as a main structural material, and also quantified the CO₂-e emissions impact and thermal performance of different concrete mixes. The results confirmed that embodied CO₂-e emissions can be reduced significantly using supplementary cementitious materials. The thermal conductivity of concrete is strongly
influenced by thermal properties of the concrete mixes and the proportions of its constituents. The results reveal there are many variations in embodied CO\textsubscript{2}-e emissions values across different inventory databases.

An uncertainty analysis was used to quantify the variations associated with the CO\textsubscript{2}-e emissions embodied in building materials and structural systems. The results reveal the contribution and variation of each type of construction material and structural systems in their whole life cycle, from the extraction of raw materials to the construction site and end of life building. The sources of uncertainty are the variations in the method of analysis used for each assessment, the different system boundaries, the sources of data, and quality of input used to calculate the upstream process.

A detailed energy simulation analysis via DesignBuilder was used to quantify the possible impact that construction forms and type of structural concrete might have on the energy consumed by the reference commercial office buildings across five Australian cities. The energy analysis revealed that the thermal capacity can be utilised to shift loads to reduce peak demand and reduce operational energy consumption if it is used as thermal energy storage.

The final part of this study is a proposed method to combine life cycle cost analysis with relative CO\textsubscript{2}-e emissions costs of a concrete structure during its lifetime. The results provide a quantitative value for evaluating the global CO\textsubscript{2}-e emissions impact made by different building structures in five Australian climate zones. The findings of this study also show that selecting an optimal structural design based on a single phase of life cycle assessment might not be the best way to choose ideal design alternatives.
Acknowledgments

Undertaking this PhD has been a truly life changing experience that would have been impossible without the support and guidance I received from many people; I am grateful to everyone who has support my journey towards this finished thesis. There are far too many to name but there are some I would like to especially thank.

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Mehdi Robati
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List of publications associated with this thesis

The following papers were produced to disseminate the concept and outcomes of the study undertaken by the author during this PhD research. This thesis is formatted as a thesis by compilation.

Chapter 4
Status: Published

Chapter 5
Status: Published

Chapter 6
Status: Published

Chapter 7
Status: Accepted (Manuscript number: ENB_2017_2644)
Chapter 1 Context statement

1.1 Research background and motivation

This study evaluates the potential effects of concrete structural systems on the lifetime performance of a building. This thesis comprises a series of papers that were published or accepted for publication to address the impact of CO$_2$-e emissions associated with the structural design of buildings. Structural engineers aspiring to minimise the carbon embodied in a building must be able to understand how structural systems integrate with other building systems over the lifetime of the building. Structural engineers can influence the performance of a building from a sustainability perspective by considering how construction methods and structural materials will affect a life cycle analysis, while structural design can look into the future by understanding how structural materials are extracted, processed, transported, and installed. When considering the whole lifetime of a building a structural engineer must consider the impact the structural system will have on the building’s thermal performance and energy usage because at the end of life process, the structural design imposes constraints on how buildings are ultimately demolished, and components are removed, reused, or otherwise disposed.

1.2 Sustainability in the structural design of buildings

Sustainability involves the interaction of environmental, economic, and social factors (as shown in Figure 1-1). With regards to the building industry, sustainability is ensuring that a building is ecologically friendly and economically feasible, as well as having a quality and healthy internal atmosphere for the occupants.
In terms of achieving a sustainable structural design in a building, the structural engineer must recognise the characteristics and implementation constraints of the design alternatives at a global scale before choosing an appropriate one. This role gives structural engineers a particular responsibility to not only consider the structural effects and responses to loads, but also the sustainability aspects of structural design. Sustainable building design uses various methods to integrate the three sustainability aspects into design and practice (Ding 2008). The following sections provide a brief description on issues related to the environmental impact, design efficiency and economic aspect in the sustainable design process of the building.

1.2.1 Environmental impact

Building construction has a very important impact on the environment because all the processes of manufacturing and transporting materials as well as installing and constructing buildings consume
a lot of energy and emit large amounts of greenhouse gas (GHG) emissions. The carbon dioxide emissions from energy consumption in buildings accounts for most of the warming impact of current human greenhouse gas emissions (Pachauri et al. 2014).

The environmental impact of a building has temporary and long-term effects; temporary effects include initial construction activities such as noise and air pollution around the site, followed by the end of construction phase, whereas long-term environmental impact includes consumption of resources and production of waste through different phases of the building (construction, operation and end of life/demolition). Major environmental impact occurs during the lifetime of a building through the consumption of resource energy and the production of waste, all of which are explained below.

1. Resource consumption

Resource consumption is increasing as the demand for new buildings and upgrade of existing ones increases; globally the construction industry consumes 40% to 50% of the total mass of materials used (Storey 2008), and since concrete is the most widely used construction material, it consumes the second highest amount of natural resources (ISO15673 2005). The construction industry also generates large quantities of waste that is often incinerated or discarded in landfill sits. In Australia, the construction and demolition industry account for significant amount of waste generated and disposed of in landfill (Crawford 2011). The environmental impact due to resource consumption is attributed to different sources, because construction materials need water, energy for manufacturing, and transportation to deliver it to the site (Miller & Ip 2013).
2. Energy usage

Energy consumption attributed to buildings consists of the energy required for manufacture, supply, construct, and use during the useful life of a project, while the energy inputs needed to produce a building, from the extraction of raw materials, on site construction and final demolition and disposal represents the embodied energy of buildings (Hammond & Jones 2008). The operational energy of a building consists of the energy used for heating, cooling, hot water, ventilation, lighting and appliances, whereas the embodied energy represents a small fraction (13% to 19%) of its operational energy over a 50 year lifetime of the building (Dimoudi, A & Tompa, C 2008). However as operational energy decreases, the proportion of embodied energy in the total energy of building may gradually become a bigger issue; indeed studies in Sweden on buildings with the lowest energy consumption show that the embodied energy for a life time of 50 years may be 45% of the total energy (Thormark 2002).

The energy footprint consists of the fusil, nuclear, and renewable energy footprint, while the embodied carbon dioxide emissions footprint describes the emissions of carbon into the air as a result of a product or service (Radu et al. 2013). The carbon footprint describes the amount of greenhouse gas emissions (GHG) or CO$_2$-e emissions produced during the life cycle of a product or system (Onat et al. 2014).

An appropriate choice of construction and building materials can possibly reduce the embodied energy and operational energy of a building. Materials with a low conductivity factors and high thermal resistances help to reduce energy consumption and associated greenhouse gas emissions (Torgal & Jalali 2011). While dense materials such as concrete cannot meet these requirements, but if the concrete is thick enough it can improve thermal performances. Concrete and masonry
products can absorb and release heat at a rate which is almost the same as a building’s daily heating and cooling cycle stored heat (observing heat during the day and releases at night). A study where structural thermal performance was monitored in real time revealed that the thermal mass of a slab/wall caused a clear lag in the indoor and outdoor temperature change (Hajdukiewicz et al. 2015).

3. Waste production

The final stage of the built environment life cycle is the demolition and disassembling of a building. Building construction and demolition produces waste through the life cycle of the building, from the construction phase, usage or maintenance phase, to the end of life or demolition phase. In fact in many countries, the waste produced from the construction and demolition area is one of the largest parts of the waste produced. In 2010, the Australian construction and demolition sector was 38% of the total waste generated, of which 33.9% was disposal (DEE 2013). Several regulations in Australia set strategic targets to minimise waste generation and maximise recovery; for example, Queensland’s Waste Reduction & Recycling Strategy seeks to increase the rate of recycling to 80% by 2024 (DEHP 2014).

During the usage and maintenance phase, not a lot of waste is produced unless renovations take place (Tam & Tam 2006), but through the construction phase, the formwork, concrete work, and masonry work typically accounts for 30%, 13%, and 13% of waste production (Poon et al. 2004). The method of construction, project size, building type, technical problems, human errors and storage method are the main elements that influence waste generation in newly constructed buildings (Mokhtar et al. 2011).
The demolition phase produces large amounts of waste, and since most demolished structures end up as waste, the need to maximise the reuse and recycling of construction and demolition waste has been introduced as selective demolition (Kourmpanis et al. 2008). Selective demolition proposes to remove the building components in the inverse direction of its construction, and while this is more time consuming and expensive (Torgal & Jalali 2011), if the full potential of selective demolition is considered at the design stage it could result in many environmental, economic, and social benefits (Thormark 2007).

4. Environmental assessment tool

The environmental assessment tool provides a framework to assess and report environmental impacts in the building sector. This framework integrates three aspects of sustainability to evaluate the long-term performance of buildings. The sustainability reporting tools are categorised into the quality assessment, life cycle analysis, and energy consumption evaluation (Berardi 2012). The quality assessment system is a multi-criterion system which integrates the three aspects of the sustainability of buildings. This system is based on assessing criteria measured by several parameters and then comparing them across the real performance as a reference one (benchmark building).

Several other multi-criterion systems have been published to assess the sustainability of buildings and quantify the environmental impacts of human activities, as evidenced by the American Leadership in Energy and Environment Design (LEED), UK’s Building Research Establishment Environmental Assessment Methos (BREEAM), Green Star in Australia, and more recently the Living Building Challenge (Ding 2004; Ding 2008; Kibert 2012). These systems are whole
building assessment systems where the frameworks are intended to iteratively assess the impact that a product, process, or service has on the environment (Cabeza et al. 2014). These assessments and rating tools are now being used to clarify the environmental impact of buildings even though they are criticised for lack of attention to the life cycle perspective and not understanding the total impact of decisions made during designing and operating the facilities (Whitehead et al. 2014).

In Australia, the National Standards Development Organisation (NSDO) is a non-profit company that developed a series of standards to specify the requirements needed to assess and declare the comparative environmental impact of building products and systems (NS11401.0 2014). NSDO proposed to use several benchmark buildings as a comparative tool to declare the environmental performance of building products and systems in buildings over their useful life (NS11401.0 2014). This benchmarking tool can help designers compare design alternatives based on their potential impact (Rajagopalan et al. 2012).

To compare the impact of different design alternatives, a life cycle assessment method can be used. A life cycle analysis assesses the materials used and the energy released by the system into the environment over the lifetime of a building; it is called “Cradle to Grave.” Several studies have pointed out the difficulty and uncertainties associated with applying whole life cycle assessment to the building sector due to different reasons— the long lifetime, size, and the intensive use of natural resources and inconsistencies inherent in estimating the environmental impact at every stage of a building (Cabeza et al. 2014; Ortiz et al. 2009; Sharma et al. 2011; Taborianski & Prado 2004).
1.2.2 Design efficiency

Another challenge for sustainable design is to improve the energy efficiency of buildings over their lifetime while reducing the environmental impact of the design. Research into sustainable structural design has attempted to address the impact that structural systems have on a building’s lifetime. Several studies have shown the impact of structural systems on the environment by considering the amount of carbon emitted through pre-use, use, and the end of buildings life (DIIS 2013; Pongiglione & Calderini 2016; Sarkisian et al. 2012; Webster 2004). Their studies showed that structural forms are responsible for 20% of the initial embodied energy and 10% of the whole building’s life cycle impact (DIIS 2013; Pongiglione & Calderini 2016; Sarkisian et al. 2012; Webster 2004). Foraboschi et al. (2014) showed that flooring systems are responsible for most of the environmental impact when incorporated with other structural components (Foraboschi et al. 2014). Moreover their study of six construction systems indicated that type of floor and balance between thickness and the number of secondary beams directly affect the total energy embodied in buildings; this means that selecting an appropriate construction system can save significant amount of total energy embodied in a building (Foraboschi et al. 2014).

With regard to the type of structural material, choosing wisely helps to minimise the carbon emissions associate with building designs; however, selection of materials should address the specific geographical and economic context in which these technologies are applied. Cold-formed steel and thin walled aluminium profiles are commonly used in the construction industry due to their efficiency, lightweight, ease of erection, and low cost (Gilbert et al. 2014; Javed et al. 2017; Mainey et al. 2015). Despite the advantage of cold-formed steel framing, there is little information available in Australian building design codes on fire ratings and sound transmission class ratings...
of cold-formed steel in mid and high rise buildings (ABCB 2015; Hancock 2007). Currently, the cold-formed steel framing is limited to six stories height (Mujagic et al. 2012).

Our advanced understanding of timber buildings demonstrates the applicability of wood as a primary structural support system in mid-rise building construction (Robertson et al. 2012; Skullestad et al. 2016), and the desire to design buildings with low carbon emissions has prompted several studies to consider timber as a part of the main structural materials (Abrahamsen & Malo 2014; Skullestad et al. 2016). Despite the advantages of a timber structure, our understanding of structural properties and safety of structural timber components is limited (Robertson et al. 2012; Schmidt & Griffin 2013). Currently, the tallest timber building is a 14-storey residential building in Norway (Ramage et al. 2017).

In Australia, concrete is the most widely used construction material and concrete structures predominantly drive the Australian building industry (Kelly 2017). Concrete is a popular material due to its excellent mechanical and durability properties, and it is adaptable, relatively fire resistant, and generally available and affordable. Recent advances in concrete technology offer lower GHG emissions by using supplementary cementitious materials and recycled aggregates. There are improvements to thermal properties by using admixtures. Concrete as a building material can have high thermal properties because it absorbs and retains energy for a long period of time. In cold seasons, high thermal mass building elements that contain concrete such as walls and floor slabs, absorb radiant heat from the sun during the day and gradually release it back into the system (space) during the night when the outside temperature drops (Lemay & Leed 2011). The ongoing developments of novel construction materials such as Ultra-lightweight concrete (Huiskes et al. 2016; Roberz et al. 2017; Yu, QL et al. 2015) which offers lower thermal conductivity and density,
raise a question about their possible impact on the lifetime thermal performances. Another question is raised regarding the relationship between the life cycle environmental impact and thermal performance during the operational phase of a building. From a low CO$_2$-e emissions design perspective, it is important to understand how to design a building structure with respect to its strength, the impact of CO$_2$-e emissions, the energy performance and the thermal comfort over its lifetime. This question is often overlooked by structural engineers.

1.2.3 Economical aspect

This combination of a lifetime environmental impact and energy performance in economic terms provides a framework to compare and evaluate the sustainability of construction solutions. To evaluate environmental sustainability, a life cycle analysis must include the performance of a building from its manufacture to its disposal. This explains why the whole building system considers the materials, site activities, consumption of energy and resources, the thermal comfort and natural resources, as well as their interfaces with each other. This approach is encouraged as a cost-saving method or life cycle cost technique which allows more money to be invested into a new building system, even though it may be expensive on the first or overall cost basis (Kibert 2012). In fact many sustainable reporting systems do not mention integrating the economic aspects into their assessments (Y. J. Siew et al. 2013). The life cycle cost is a useful method in the design process to determine which system provides the maximum net saving when alternative choices provide the same performance requirements but varying with regards to the initial costs and operating costs (Fuller 2016; Harris et al. 2017). From a life cycle perspective, it appears that the economic driver is not only the initial cost, but also the operational, maintenance, and repair costs
are also important (Harris et al. 2017). The life cycle cost method attempts to establish a trade-off between the initial cost and long-term cost of alternative design solutions (Robinson et al. 2015). The life cycle cost analysis is a useful tool, but there is a need to examine the integration framework to consider the environmental impact, design efficiency, and economical aspect in the decision making process.

In response to the concerns raised, this research program seeks to explore the potential impact of low CO$_2$-e emissions structural design over the lifetime of a building. The scope of this PhD is to evaluate the effect of structural concrete and construction methods on the consumption of energy and resources over the lifespan of a building. It focuses on how low CO$_2$-e emissions in structural design is achievable, and how it can directly relate to sustainability in the built environment.

1.3 Aims and objectives

The primary aim of this research is to investigate the impact of concrete structural systems on sustainability of buildings. It mainly focuses on the life cycle of a building by considering lifetime energy performance, carbon dioxide emissions and cost, i.e., cradle to grave.

This study investigates the potential CO$_2$-e emissions impact associated with various types of concrete and construction systems. To achieve this end, a benchmarking method is used to compare and measure how structural design alternatives affect the lifetime impacts of a building; specifically, the life cycle CO$_2$-e emissions impact associated with a typical office building in Australia.

This research seeks to develop a framework that will include a life cycle assessment in the structural design of buildings. This framework will demonstrate how different design alternatives affect the
whole of life carbon emissions, energy consumption, materials used, and life cycle cost in a building. To achieve this goal, the research is classified into the following primary objectives:

1- Review existing literature in sustainability and then identify the main key strategies, parameters, and tools associated with structural design;

2- Investigate the relative impact that the properties of selected concrete materials will have on CO2-e emissions at the initial stage of structural design;

3- Investigate the effect of uncertainty on the impact of carbon emissions that each construction material has on a typical high-rise office building;

4- Investigate the relative contribution of structural concrete and construction forms to the lifetime energy demand and thermal performance of office buildings;

5- Develop a life cycle assessment model of several office buildings as benchmark buildings.

6- Propose a global assessment parameter as a result of whole life CO$_2$-e emissions, and structural costs during the lifetime of buildings.

1.4 Research question

The key questions for this research are:

➢ How is sustainability defined in structural design?

➢ How do we measure the effects of equivalent concrete structural system on the life cycle of buildings?

➢ Can structure and structural design play a significant role in the life cycle of buildings?
➢ What is the impact of structural materials and construction systems over the lifetime environmental impact, the energy performance and cost of a building?
➢ Can life cycle assessment be applied to the structural design and construction method?

1.5 Research method in brief

This research builds on the existing mix-assessment method to investigate the research questions from various perspectives. In the first stage, current literature is used to identify significant variables for the low carbon design of buildings; in the second stage, carbon emissions impacts associated with type of concrete as a structural material are analysed by collecting a number of concrete mix designs from published literature; in the third stage, a comparative method is used to compare the impact of carbon emissions associated with various construction forms and building materials by considering a typical concrete benchmark building in Australia. The results from this stage were then reprocessed through the uncertainty assessment method to quantify the variations associated with the carbon emissions from the study parameters. In the fourth stage, an energy analysis method is used to identify the potential impact of structural alternatives on the energy usage and thermal performance of the benchmark office building. This stage identifies the impact made by construction forms and the properties of structural concrete (Ultra-lightweight, normal weight). In the final stage, a framework is developed to describe the lifetime impact of CO2-e emissions associated with the structural design of a building in form of a single dimensional parameter which describes lifetime of CO2-e emissions and construction costs associated with
various design alternatives at the initial stage of the decision-making process. The contextual value of these conclusions are based on the finding from these multi-analysis approaches.

1.6 Structure of thesis

The outline of each Chapter is as below, and the location of the linking Chapters with specific research objectives is shown in Figure1-2.

Chapter 1 provides the background information pertaining to this study. It describes the main intention of this research by highlighting the research aims and objectives; it also provides research questions and an overview of the method used to conduct this research.

Chapter 2 reviews the literature and previous studies on sustainability and sustainable structural design of buildings. This Chapter highlights the sustainability aspects and the sustainability principles in building design. It also covers the common techniques and solutions for quantifying energy performance and minimising the carbon dioxide emissions from buildings. This Chapter points out the research gap in incorporating life cycle assessment tools with the structural design of buildings.

This is followed by a review of the sustainability reporting tools, life cycle sustainability assessment for energy consumption, life cycle assessment tools, and databases.

Chapter 3 presents the methodology used to integrate the life cycle assessment approach into the structural design of buildings. To illustrate the potential impact of CO2-e emissions on concrete structural systems, the benchmark building was used to compare the results of energy analysis and CO2-e emissions based on different design alternatives.
Chapter 4 incorporates a carbon dioxide emissions evaluation (CO2-e emissions) and the thermal properties for various concrete mix designs. This Chapter also compares the impact of selecting a concrete mix design in terms of embodied carbon dioxide emissions (CO2-e emissions) with resulting thermal conductivity and density at the design stage of buildings.

Chapter 5 develops an uncertainty analysis model to quantify the variations associated with the calculation of CO2-e emissions. This Chapter uses a benchmark building to compare the uncertainty associated with the impact of CO2-e emissions in four different construction forms.

Chapter 6 contains the energy analysis and thermal performance of an Australian benchmark office building and estimates the impacts of selecting various structural concrete and construction forms.

Chapter 7 provides a framework to integrate the results of a life cycle assessment as a single parameter to enhance the decision-making process at the early stage of building design. This Chapter compares the total life cycle CO2-e emissions and building costs associated with two different construction forms and types of concrete across five major cities in Australia.

Chapter 8 summarises the work presented in this thesis and outlines the contribution to the knowledge of this field; it also presents several recommendations for future research.
Figure 1-2 Locations where Chapters with specific research objectives are linked
Chapter 2

Literature review

2.1 Introduction

The previous Chapter introduced the main issues to consider with sustainable building design because sustainable buildings have now become a multi-disciplinary research investigation. From a structural design perspective, a concern is how to develop a decision-making process that will reduce the negative impacts on the natural environment. This means understanding the main strategies, parameters, and tools associated with sustainable building. This Chapter is a review of the available literature and a presentation of the fundamental concepts related to this research, including an identification of the factors which influence low carbon dioxide emissions structural elements, as well as the recognised methods and technologies used to reduce the CO2-e emissions of building structures such as sustainability reporting tools, protocols, and standards. The key knowledge areas of this research are shown in Figure 2-1.
2.2 Sustainability in structural design

In terms of moving towards sustainability in structural design, a structural engineer must clearly understand the characteristics and constraints of the design alternatives at a global scale before choosing an appropriate one. This role gives structural engineers a particular responsibility to not only consider the structural effects and responses to loads, but also considers the environmental, economic, and social aspects of structural design while working to reduce the side impacts of the proposed design.
Research into sustainable structural design strives to address the impact that structural systems have on various aspects of sustainability, such as the environment, economy and society, which is why some researchers propose various principles of sustainable construction. In 1994, Kibert developed six principles for sustainable practices in civil engineering practices: minimise resource consumption, maximise resource use, use renewable/recycle resources, protect the natural environment, create a healthy, non-toxic environment, and pursue quality in creating the built environment (Kibert 1994). In 2004, Maydl pointed out the significance of a holistic approach for civil engineers to reduce the impact of building structures (Maydl 2004). Early studies attempted to quantify the effects of structural forms to the energy usage of buildings (DIIS 2013; Pongiglione & Calderini 2016). Their studies showed that the structural forms are responsible for 20% of initial embodied energy (DIIS 2013). Webster (2004) studies on three buildings (located in Canada and the USA) revealed that the structural forms could account for 10% of the whole building life cycle impact. Several other studies argued that by moving towards minimising the operational energy, the environmental impacts associated with manufacturing and construction will become even more important (Pongiglione & Calderini 2016; Sarkisian et al. 2012; Webster 2004).

A number of studies highlighted the social and economic aspects of sustainability in structural design (Fernando et al. 2012; Kang & Kren 2007; Pongiglione & Calderini 2016). For instance, Fernando et al. (2012) categorised the environmental, economic, and social impact of bridge structures. The environmental impact consists of embodied CO₂-e emissions; the economic impact considers the costs associated with materials, equipment and property damage; the social impacts considers the risk of injury or death (Pongiglione & Calderini 2016).
Meanwhile, Alimoradi (2014) points out conflicts between some sustainable practices and some fundamental questions (Alimoradi 2014). Alimoradi’s questions introduced more general problems with sustainable structural design with concerns about prioritising the impacts to be covered, the strategies to be developed, and methods used to evaluate (Pongiglione & Calderini 2016). Pongiglione and Calderini (2016) formulated these points into a single question: “What are the essential features and steps needed to achieve a sustainable structural design” (Pongiglione & Calderini 2016). The following sections address this concern by focusing on sustainable design strategies and parameters as well as exploring the role structural engineers play in sustainable rating tools.

2.3 Sustainable structural design strategy

Sustainable structural design strategy is a method of selecting structural materials and forms to reduce their impact (Pongiglione & Calderini 2016). Since recognising the impact that building structures have on the environment, the economy, and society, several studies began to develop tangible design strategies to reduce this impact. Danatzko and Sezen (Danatzko & Sezen 2011) proposed several strategies for sustainable structural design as follows:

- Minimising material production energy by only selecting materials where the manufacturing process allows for resource and energy saving. This method can be used to conserve natural resources and reduce embodied emissions.
- Minimising embodied energy by providing for lower embodied energy and CO2-e emissions.
- Minimising material use by reducing the quantity of materials used in a building structure.
- Life cycle assessment as a decision making tool to compare the impact associated with different design alternatives.

- Maximising structural system reuse by using recovered structural materials and members. Anderson and Silman (2009) also proposed a different classification to address the reduction of embodied CO\textsubscript{2}-e emissions associated with a building structure. Their classification includes (1) Design for efficiency, (2) Design for materials, (3) Design for energy, (4) Design for adaptability and (5) Design for recycling (Anderson & Silman, 2009; Pongiglione & Calderini, 2016). A comparison of these two proposed classifications shows some overlap between them; Table 2-1 compares the two proposed structural design strategies.

**Table 2-1 Compares two proposed structural design strategies (adopted from (Pongiglione & Calderini 2016))**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Adaptability</td>
<td>----</td>
<td>Design for adaptability</td>
<td></td>
</tr>
<tr>
<td>Reuse</td>
<td>Maximising structural system reuse</td>
<td>----</td>
<td></td>
</tr>
<tr>
<td>Design for reuse and recycling</td>
<td>----</td>
<td>Design for recycling</td>
<td></td>
</tr>
<tr>
<td>Low embodied energy and CO\textsubscript{2}-e emissions</td>
<td>Minimising materials production energy</td>
<td>Design for materials</td>
<td></td>
</tr>
<tr>
<td>Minimising materials</td>
<td>Minimising materials use</td>
<td>Design for efficiency</td>
<td></td>
</tr>
<tr>
<td>Minimising energy use</td>
<td>Minimising embodied energy</td>
<td>Design for energy</td>
<td></td>
</tr>
<tr>
<td>Life cycle assessment</td>
<td>Life cycle analysis/inventory/assessment</td>
<td>----</td>
<td></td>
</tr>
</tbody>
</table>
2.4 Sustainable structural design parameters

The sustainable structural design must have quantitative and accountable parameters; for instance, the parameters used to measure strategies to mitigate the impact of resources reduction are expected to be the usage of none renewable energy or raw materials, but not the impact of embodied CO\textsubscript{2}-e emissions (Pongiglione & Calderini 2016). Parameters which assess sustainable structural designs are still in progress (Hong et al. 2012). Traditionally, the structural design of buildings was limited to optimising cost and weight parameters (Moon 2008), but new approaches now provide frameworks to integrate the long-term impact of materials and systems into the design process. For instance, several studies pointed towards assessing the sustainability of structures based on their environmental impact (Hong et al. 2012; Moon 2008; Roaf et al. 2009), their embodied energy (Crawford 2011; Foraboschi et al. 2014; Jiao et al. 2012; Yokoo et al. 2013), their embodied CO\textsubscript{2}-e emissions (Anderson & Silman 2009; Islam, H. et al. 2015; Oh et al. 2016; Yepes et al. 2015) and the use of a momentary element to address the environmental and structural characteristics during the lifetime of buildings (Tsimplokoukou et al. 2014).

2.5 Quantifying the sustainability in buildings

Measuring the environmental impact in the building could be a complicated task at the design and construction stage. However, building sustainability reporting tools could be used to build up a score of building performances against the sustainability criteria. Sustainable reporting tools are present industry standard guidelines which allow for comparisons across different projects (Y. J. Siew et al. 2013). The building sustainability reporting tools are categorised as an assessment of
total quality, life cycle analysis and energy consumption (Berardi 2012). The following section reviews those tools presently available for evaluating and reporting sustainability in the building.

2.5.1 Standardisation work on sustainable construction

The International Organisation for Standardisation (ISO) and European Committee for Standardisation (CEN) has attempted to define an objective for sustainable construction and provide a common framework to compare the results. The ISO technical committee provides several specifications and standards for the environmental and sustainable assessment of buildings. These standards and specifications include a sustainability indicator (ISO21929-1 2016), an environmental declaration of products (ISO21930 2007), general principles (ISO15392 2008) and frameworks to assess the environmental performance of construction work (ISO21931-1 2010).

In parallel with ISO, CEN has published standardised approaches for measuring sustainability in construction. The CEN technical committee provides standardised methods for evaluating the sustainable aspects of new and existing construction activities as well as several standards for declaring the environmental products that form part of construction products. Figure 2-2 summarises the European standard publications for assessing the sustainability of buildings (Rossi 2014).
Similarly, European United provides regulations and policies to improve the environmental performance of buildings by including eco-friendly and energy efficient materials. Their publications are classified into the following parts:

- Energy Labelling Directive (energy related products)
- Energy Performance Building Directive (EPBD)
- Energy Performance Building Directive (energy related products)
- Energy efficiency action plan
- Ecolabelling Regulation
- Ecolabelling for Buildings
- Green Public Procurement
- Construction and Demolition Waste
- Resource efficiency road map

The resource efficiency report suggests that existing policies in the building industry, which primarily focus on energy efficiency, also need to integrate resource efficiency (EC 2014) because they consider the ecological impacts and resource usage during the lifetime of buildings (EC 2014).

### 2.5.2 Environmental footprint schemes

In line with ecological sustainability, various tools have emerged to address a unified footprint method for the environmental impact of production and consumption (Galli et al. 2012). The European commission has presented two methods for assessing the environmental footprint associated with products and organisations (Galli et al. 2012; Tsimplokoukou et al. 2014). The environmental footprint of a product (PEF) applies to individual products or services, whereas the organisational environmental footprint (OEF) studies organisational activities as whole and considers all the activities associated with the product and services of organisations from the supply-chain (from extraction of raw materials through to the manufacturing process, usage, and end of life)(EC 2013).
The aim of these two publications (PEF and OEF) is to establish a common method to assess, display, and benchmark the environmental performance of materials, services, and companies in accordance with a comprehensive ecological assessment over the life cycle of a building (EC 2013). The plans for an environmental footprint consist of energy and water consumption, embodied carbon emissions, and waste production (Tsimplokoukou et al. 2014). The environmental footprint represents a quantitative potential life cycle environmental impact of a specific product in the form of a single indicator (Čuček et al. 2012).

The energy footprint consists of the fusil, nuclear, and renewable energy footprint, while the embodied emissions footprint describes the emissions of carbon into the air as a result of a product or service (Radu et al. 2013). The carbon footprint describes the amount of GHG emissions or CO$_2$-e emissions produced during the life cycle of a product or system (Onat et al. 2014). There are three main international standards to address the carbon footprint associated with products and services, and they are known as the Publicly Available Specifications (PAS) 2050 (PAS2050 2011), the GHG Protocol Products Standard (Protocol 2011) and ISO 14067 (ISO14067 2013). Along with those three standards, ISO 14067 also aims to provide a standardisation line on the carbon label to enhance comparable and reliable carbon plans in the future (Wu et al. 2014).

In summary, Figure 2-3 and Figure 2-4 summarise the relationship between life cycle assessment, and the GHG standards PEF and OEF.
Figure 2-3 Relationship between LCA, GHG Standards and PEF method (EC 2013; Tsimplokoukou et al. 2014)

Figure 2-4 Development of the OEF method based on International methodologies (Ding 2004; EC 2013)
2.5.3 Energy rating tool

Several multi-criterion systems have been published to assess the sustainability of buildings and quantify the environmental impact of human activities, as evidenced by the American Leadership in Energy and Environment Design (LEED), UK’s Building Research Establishment Environmental Assessment Method (BREEAM), Green Star in Australia, and more recently, the Living Building Challenge (Ding 2004; Ding 2008; Kibert 2012). These reporting tools review different phases of a project and provide guidelines for the design (as shown in Table 2-2). These tools use viewpoint and performance based criteria to evaluate existing and new construction buildings. Third parties are used to verify the final results of all the tools, as noted by Y. J. Siew et al. (2013).

Table 2-2 Analysis of sustainable reporting tools (CASBEE 2016; GBCA 2014; Kibert 2012; LEED 2012; Nguyen & Altan 2011; Y. J. Siew et al. 2013)

<table>
<thead>
<tr>
<th>Item</th>
<th>BREEAM</th>
<th>LEED</th>
<th>CASBE</th>
<th>Green Star</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage of Project</td>
<td>Design, review and construction</td>
<td>Design, construction and operation</td>
<td>Preliminary design, design, and post design</td>
<td>Design, review and as built</td>
</tr>
<tr>
<td>Offer training and certification</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Use viewpoint and performance based criteria</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Existence of different systems (existing building, new construction, ...)</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Provision of case study and manuals</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Third party verification</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>End product presentation</td>
<td>Percentage of credits achieved (%)</td>
<td>Total Score</td>
<td>BEE graph</td>
<td>Total score</td>
</tr>
</tbody>
</table>

Note: × shows the presents of an attribute
The final presentation of a project can be in the form of a graph (such as a BEE graph for CASBEE), the percentage of archived credit (such as BREEAM), and the total score (like LEED and Green Star).

These four sustainable reporting tools for buildings are scored against criteria such as: Availability, Popularity, Methodology, Applicability, Accuracy, Data collection process, User friendly, Development, and Presentation. Table 2-3 compares the overall score for four sustainable reporting tools.

**Table 2-3 Overall score of four sustainable reporting tools (Nguyen & Altan 2011; Y. J. Siew et al. 2013)**

<table>
<thead>
<tr>
<th>Attributes</th>
<th>LEED</th>
<th>BREEAM</th>
<th>CASBEE</th>
<th>Green Star</th>
</tr>
</thead>
<tbody>
<tr>
<td>Popularity (out of 10)</td>
<td>10</td>
<td>10</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>Availability (out of 10)</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>Methodology (out of 15)</td>
<td>10</td>
<td>11</td>
<td>13</td>
<td>9</td>
</tr>
<tr>
<td>Applicability (out of 20)</td>
<td>13</td>
<td>13</td>
<td>11.5</td>
<td>10</td>
</tr>
<tr>
<td>Data collection process (out of 10)</td>
<td>7</td>
<td>7</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>Accuracy (out of 10)</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>5</td>
</tr>
<tr>
<td>User friendly (out of 10)</td>
<td>10</td>
<td>8</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>Development (out of 10)</td>
<td>8</td>
<td>8</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>Presentation (out of 5)</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Final Score (out of 100)</td>
<td>75</td>
<td>75</td>
<td>69.5</td>
<td>65</td>
</tr>
</tbody>
</table>

The advantage of different sustainable reporting tools is summarised in Table 2-4.
Despite their advantages, these building sustainable reporting tools have been criticised for not considering the lifetime impacts of buildings (Y. J. Siew et al. 2013), and for not incorporating the financial aspects by assessing projects, as well as imposing non-scientific benchmarks (being too idealised) (Ding 2008; Mitchell 2010; Sharifi & Murayama 2013; Y. J. Siew et al. 2013).

The literature suggests several points to enhance building sustainable reporting tools:

- Y. J. Siew et al. (2013) suggests expanding the list of criteria to include more measurable economic and social issues.
- Y. J. Siew et al. (2013) suggests considering the life cycle effect of buildings based on sustainable reporting tools.
- Mitchell (2010) suggests integrating building performance tools with the potential environmental impact report in order to obtain a reliable result about the decisions made.
• Kestner et al. (2010) suggests applying some changes to allow more engineering disciplines to contribute to the sustainability of projects.

2.5.4 Benchmarking process

Energy benchmarking uses data to measure the energy performance of a building over time and then compare the results across similar buildings. Building benchmarking can reveal the energy efficiency of a building by indicating its energy performance (Shahrestani et al. 2014). Benchmarking aims to identify the right action where great savings can be made (Bosteels et al. 2010), which means evaluating the building energy efficiency by comparisons with standards or established energy benchmarks.

Pérez-Lombard et al. (2009) suggests four steps in the benchmarking process, as shown in Figure 2-5. Firstly, provide a database with information about energy performance, the type of building, and the size of a significant number of buildings which can be extracted from available literature, and from commercial and non-commercial databases. Secondly, evaluate the energy performance of the case study by collecting relevant information, and thirdly, quantify the quality of the case study by comparing the results of an energy performance analysis against the samples held in the databases. Lastly, the compression result shows the feasibility of energy strategy from both the technical and economic points of view (Pérez-Lombard et al. 2009).

Figure 2-5 Building energy benchmarking process (Pérez-Lombard et al. 2009)
There are two models where a database can be used to establish statistical benchmarks, the simple normalised model and the regression model. The normalised model uses an energy performance indicator such as the floor area where normalised energy uses intensity to account for one feature that affects the energy performance of a building (Wang et al. 2012), while the regression model considers the effects of other energy usage factors for the energy performance of the benchmark building (Wang et al. 2012).

In terms of benchmarking a certain building by simulation, implementing a self-reference building as the comparison criteria is preferable because a self-referencing building is presented as the total identical buildings in terms of geometrical dimensions, shape, functional layout (Wang et al. 2012). This method has been adapted to evaluate the energy performance of both new and existing buildings across different environmental schemes and energy certifications. Generally, the performance of an asset building is determined by the percentage of annual energy reduction of a building in relation to a reference building. Figure 2-6 shows a different assessment scale for classifying the energy performance of a building.

<table>
<thead>
<tr>
<th>HEBAEM</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEED</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>BREEM</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td>CAILER</td>
<td>C</td>
<td>D</td>
<td>E</td>
<td>F</td>
<td>G</td>
<td>H</td>
<td>I</td>
<td>J</td>
<td>K</td>
<td>L</td>
<td>M</td>
</tr>
<tr>
<td>CEN</td>
<td>B</td>
<td>C</td>
<td>D</td>
<td>E</td>
<td>F</td>
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<td>H</td>
<td>I</td>
<td>J</td>
<td>K</td>
<td>L</td>
</tr>
</tbody>
</table>

**Figure 2-6 Energy performance assessment scales using self-reference benchmarks (Wang et al. 2012)**
2.5.5 Life cycle sustainability analysis

The demand in developing methods to improve understanding and address the impact and benefit of the product during its lifetime has led to in life cycle sustainability assessment (LCSA). The LCSA has recently developed methods to evaluate the environmental, economic and social impact of product life cycles by integrating the three LCA tools, environmental life cycle assessments (E-LCA), life cycle cost assessment (LCCA) and social life cycle assessment (S-LCA) (Finkbeiner et al. 2010). The general concept formulates (Equation 2-1) of LCSA are given as a summation of ELCA, ELCC and SLCA (Kloepffer 2008; O’Brien et al. 1996).

\[
\text{LCSA} = (\text{E-LCA}) + (\text{LCCA}) + (\text{S-LCA})
\]  

(2-1)

LCSA = Life Cycle Sustainability Assessment  
E-LCA = Environmental Life Cycle Assessment  
E-LCC = Life Cycle Cost Assessment  
S-LCA = Social Life Cycle Assessment

The Life Cycle Cost Assessment (LCCA) and Social Life Cycle Assessment (SLCA) follow Environmental Life Cycle Assessment (ELCA) which is based on Environmental Life cycle Assessment procedure, as given in the ISO 14040 series (Klöpffer & Grahl 2014). Development under the Environmental Life Cycle Assessment differs from the substantiality aspects because the environmental aspects can be covered by Environmental Life Cycle Assessment (Cabeza et al. 2014; Takano et al. 2014), while economic and social aspects still demand essential research progress (Finkbeiner et al. 2010; Kloepffer 2008). In the following section, a literature review has been carried out on the Life cycle cost and environmental assessment by focusing on the building and construction industry.
2.6 Life cycle cost assessment

Life cycle cost assessment defines all the costs associated with the lifetime of a building, including owning and operating a facility over a period of time (Hunkeler et al. 2008; Mearig et al. 1999). For the building industry, a number of studies have tried to optimise the structural design of buildings by considering the economic and environmental aspects. These studies have proposed a conceptual framework (called “Eco-efficiency method”) to measure the sustainability of buildings by simultaneously selecting the optimal product design and considering its environmental and cost characteristics (Cha et al. 2008; Hahn et al. 2010; Ji et al. 2014; Saling et al. 2002). Others have proposed a method to evaluate the environmental impact and economics by converting embodied CO2-e emissions into a momentary term (Gu et al. 2008; Hong et al. 2013; Itsubo & Inaba 2003; Ji et al. 2014; Kim, J et al. 2012). For example, several studies on structures and construction materials as products, have evaluated the environmental impact and cost effect over various stages of the life cycle (Chou & Yeh 2015; Huang et al. 2009; Silvestre et al. 2014). According to Cabeza et al. (2014), a combination of the life cycle cost analysis with the life cycle environmental impact provides a better understanding of the total impact of a proposed project or policy (Cabeza et al. 2014).

2.7 Environmental life cycle assessment

An Environmental Life Cycle Analysis (LCA) is an assessment to identify and evaluate the environmental aspects of a product throughout all the activities during its life (ISO14040 2006). This method assesses the materials used and energy released by the system to the environment; it
is called “Cradle to Grave” and includes the extraction of raw materials, production processes, transportation, and the use and disposal depicted in Figure 2-7 (ISO14040 2006).

**Figure 2-7 Life cycle assessment stages (Cradle to Grave)**

The last version of ISO14040 (2006) defines four phases for any LCA, these phases are definitions of the goal and scope, analysis of the inventory, and impact assessments and interpretations (as shown in Figure 2-8). The definitions of the goal and scope state the purpose of the study and the boundaries of the system. The inventory analysis identifies and quantifies the amount of materials and energy inputs and outputs of a system, while the impact assessment characterises the inventory flows in the form of an environmental impact. This stage consists of three fundamentals that include the impact categories, classification of life cycle inventory, and modelling the category characterisation. Classifying the results of the life cycle inventory involves assigning the emissions, waste, and resources used to the impact categories chosen; the final result of the life cycle inventory assessment becomes the characterisation (indicator) result. This combination of environmental impact and scope of LCA study is summarised at the interpretation stage, while the last stage summarises the results for the conclusions, recommendation, and decision making (ISO14040 2006; Karimpour et al. 2014).
Two methods are used to assess the life cycle impact, these include the damaged oriented methods (end points) and the problem oriented methods (midpoints) (Bengtsson & Howard 2010). The problem oriented approach (Midpoint impact category), translates impacts into 15 environmental themes such as climate change, acidification, and human toxicity, etc., whilst the damaged oriented method (endpoints) classifies flow into different environmental themes which demonstrate the damage caused by each theme to the recourse, the natural environment, and human beings (as shown in Figure 2-9) (Bengtsson & Howard 2010).
Figure 2-9 Overall scheme of life cycle impact assessment (Bengtsson & Howard 2010)

The problem oriented impact and the damaged oriented impact can be evaluated by different assessment methods, as summarised in Table 2-5.
### Table 2-5 Environmental impact assessment methods (Bengtsson & Howard 2010)

<table>
<thead>
<tr>
<th>Method</th>
<th>Included</th>
<th>Boundary</th>
<th>Place</th>
<th>Time frame</th>
</tr>
</thead>
<tbody>
<tr>
<td>AusLCI and ALCAS best practice guide</td>
<td>• Global impacts: global warming, resource depletion, and ozone depletion</td>
<td>Midpoint</td>
<td>Australia</td>
<td>Related to which indicator is considered</td>
</tr>
<tr>
<td></td>
<td>• Regional impact: human and eco toxicity, land use, water use, soil salinization, photochemical smog</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IMPACT2002+</td>
<td>• Human health (as lack of illness)</td>
<td>Midpoint</td>
<td>Western Europe</td>
<td>Infinite</td>
</tr>
<tr>
<td></td>
<td>• Ecosystem health (potentially affected fraction of species)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Resources (impact on human and ecosystem health)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Climate change (greenhouse gases emitted per person per year)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eco-indicator 99</td>
<td>• Human health (as lack of illness)</td>
<td>Endpoint</td>
<td>Europe</td>
<td>Around 200 years</td>
</tr>
<tr>
<td></td>
<td>• Ecosystem health (potentially affected fraction species)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Resources (impact on human and ecosystem health)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EPS v2000</td>
<td>• Human health (as broad sense, eg WHO)</td>
<td>Endpoint</td>
<td>Global</td>
<td>Infinite</td>
</tr>
<tr>
<td></td>
<td>• Ecosystem production capacity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Biodiversity</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>• Recreational values</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>• Abiotic resources</td>
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</tbody>
</table>

### 2.8 Environmental Life cycle assessment in building sector

Applying a life cycle assessment to the building sector is unique in life cycle assessment practice (Ortiz et al. 2009; Taborianski & Prado 2004), not only because of the complexity, size, and intensive use of natural resources across all stages of building, but also because the following factors make this sector exclusive in comparison to other complex products (Sharma et al. 2011).
Firstly, buildings often last for more than half a century so it is difficult to predict the whole lifetime impacts of a project from cradle to gate (Cabeza et al. 2014). Secondly, since most of the environmental impact of a project occurs during the operation phase, the initial stage of design and the selection of materials is critical in order to reduce those impacts (Kibert 2012). Thirdly, during the lifetime of a project the building may undergo many changes in terms of form and function, which can be more significant than the original product (Stephan & Crawford 2014), so they should be considered at the early stage of design to minimise the environmental effects of changes (Crawford 2011), and finally, there are many stakeholders and shareholders involved in the building industry.

The European standards Technical committee (CEN) TC350 has published a series of standards to define the cradle to grave environmental impact of buildings (Moncaster & Symons 2013) and construction works (De Wolf et al. 2017) (as shown in Figure 2-10).
Figure 2-10 Building life cycle assessment stages (Cradle to Grave) defined by EN 15978 (De Wolf et al. 2017)

Figure 2-10 shows how the different stages of the building life cycle assessment are organised. The product stage covers the supply of raw material (A1), the transportation of materials from extraction to manufacturing plant (A2), and the manufacturing process (A3). The construction process phase includes transport from the manufacturer’s gate to the construction site (A4), as well as the construction process (A5). The use phase covers the time from completion of the construction work to the end of life deconstructed/demolition stage. The use stage consists of the impact arising from the use of components (B1), maintenance (B2), repair (B3), replacement (B4), and refurbishment (B5). The operational stage energy (B6) and water (B7) includes the energy and water used by the building during its operational lifetime. The end of life phase consists of deconstruction and demolition (C1), transport from site to landfills or recycling facilities (C2), and waste processing (C3) and disposal (C4). Beyond the system boundary (cradle to grave), stage D
represents the benefits and loads of components for reuse, materials for recycling, and energy recovery for future use.

Based on EN 15978 (EN15978 2011), the data associated with life cycle assessment must be recent and be geographically coherent with the location for production (which is rarely the case due to lack of databases (Dixit et al. 2012)). Data are also needed to correspond to the system boundaries set for future assessment (De Wolf et al. 2017).

According to usage, buildings can be categorised as residential and non-residential; residential buildings are either single or multiple family houses and non-residential building are those used for multi-purposes such as public buildings, office buildings, and industrial and commercial buildings (Sharma et al. 2011).

### 2.8.1 Life cycle assessment for residential buildings

The result of a study the life cycle assessment of buildings shows that the occupancy phase of buildings is responsible for 70% to 90% of the total environmental impact (Asdrubali et al. 2013), while another study of high and low populated building indicated that the structures of buildings, windows, bricks and drywalls are in the main contributors of embodied energy and greenhouse emissions (Norman et al. 2006). A study on the demolition phase of buildings in Italy showed the advantage of waste recycling in sustainability of building in terms of the environment and energy (Guggemos & Horvath 2005). Indeed the available literature reveals that the operational phase of buildings is responsible for 80% to 85% of life cycle energy consumption of buildings (Richman et al. 2009; Sharma et al. 2011).
2.8.2 Life cycle assessment for non-residential buildings

Junnila and Horvath (2003) studied on environmental impacts of office buildings over a 50 year project lifetime (Junnila & Horvath 2003). They considered a building in Finland with one kWh/m²/year as a functional unit, and then considered three phases of life cycle assessment (inventory analysis, impact assessment and interpretation of results) to define the most important aspects of building and building materials. The result of this study shows that electricity usage has the biggest impact because it is mainly used for heating, lighting, HVAC through manufacturing and maintenance of steel, concrete and paint, structure, and office waste (Junnila & Horvath 2003).

Scheuer et al. (2003) studied the life cycle performance of a six storey office building (7,300 m²) with a 75 year lifetime. Their results showed the initial energy intensity over the life of the building as 316 GJ/m² and electricity with a HVAC system accounted for 94.4% of the life cycle energy consumption of the building.

Kofoworola and Gheewala (2009) evaluated the life cycle performance of a 38 story office building in Thailand. The function unit of this study was carried out as the gross floor area (60,000 m²) of the building over a 50 year lifetime. This study considered its whole of lifetime impacts (materials production, consumption, construction, operation, maintenance, demolition and disposal). The results showed that steel and concrete are the most significant materials in terms of energy use and the environmental impact at the manufacturing phase. The whole life cycle environmental impact was dominated by the operational stage, which was 71% of total photo oxidants, 66% of total acidification, and 52% of global warming.
2.8.3 **Quantify environmental life cycle assessment in building**

The environmental life cycle assessment method can be quantified by the relative energy sequestered and expended through different life cycle stages of a building. A life cycle energy analysis is an approach that assesses lifetime building energy inputs to the building systems. The life cycle energy assessment concept can be used to illustrate the lifetime benefits of a strategic design to minimise the operational energy and embodied energy of buildings (Cabeza et al. 2014). Building life cycle energy system can classify the energy as embodied energy, operational energy and end of life embodied as shown in Figure 2-11.

![Figure 2-11 Boundary of a Life cycle energy system, adopted from (Dixit et al. 2010)]
2.8.4 The energy embodied in a building

There are different approaches to this definition due to the extraction of raw materials to the factory gate (A1-A3: cradle to gate), the extraction of raw materials to the site work (A1-A5: cradle to site), and the extraction of raw materials to the demolition and disposal phase (A1-C4: cradle to grave) (Torgal & Jalali 2011).

In the first scenario (A1-A3: cradle to gate), the energy needed for transport and the energy executed in the work are both considered as the construction phase energy consumption of the building. In this case, the embodied energy represents 85% to 95% of the total energy of materials and the remaining 5% to 15% belong to the construction, maintenance, and demolition of the building. The last scenario (A1-C4: cradle to grave) shows the necessity of using local materials because of variations in embodied energy across different modes of transport (plane, Highway, Railway, boat) (Berge 2009).

Although extensive studies have been carried out on embodied energy and carbon assessment, further studies are needed to address the significant of emissions that influence the accuracy of the life cycle assessment in buildings. The following section summarises the research undertaken to quantify embodied energy and CO₂-e emissions associated with building and building materials.

5. Building scale

This review of literature considered variations in the embodied energy of materials across different types of buildings, regions, and sources of data; as an example, Langston (2008) evaluated the initial embodied energy of thirty completed buildings in Melbourne, Australia. These case studies are a random mix across a broad range of functional purposes, including office workplaces, health
facilities, residential and educational buildings, as well as commercial and hotel accommodation.

The results indicate that the initial embodied energy varies across different types of buildings, for instance the initial embodied energy of the case studied office buildings changed from 60,326 GJ to 121,541GJ as the total gross floor area increased from 2,543 to 4,704 square metres. In the other words, the average initial embodied energy of the office building is 27.77 GJ per m$^2$ gross floor area (Langston & Langston 2008).

Ding’s (2004) research on twenty educational (high school) projects in New South Wales, Australia shows that the initial embodied energy across all the projects is 8.05 GJ/m$^2$ (Ding 2004), while on the other side of the world, Chang (2012) shows the embodied energy for a 21 storey educational building is 6.3 GJ/m$^2$ (Chang et al. 2012). Oka and Suzuki (1986) studied the embodied energy of office buildings in Japan by collecting the data from 10 buildings. The results of their study show that the energy required to construct 1 m$^2$ of floor area varies from 6.5 to 13 GJ/m$^2$ with an average value of 8.9g GJ/m$^2$ (Suzuki & Oka 1998).

Treloar (1993) and Tucker (1993) showed that the embodied energy for an office building in Australia vary from 8 GJ/m$^2$ to 9GJ/m$^2$ (cited by Treloar 1996b), while Cole (1996), Oka (1993), and Treloar (1993) showed that the embodied energy of commercial buildings vary 4.3 GJ/m$^2$ to 19 GJ/m$^2$ (cited by (Ding 2004)).

6. Building materials

In terms of construction materials, making the appropriate choices can reduce the embodied energy of a building by 17% (Thormark 2006), and reduce carbon dioxide emissions by almost 30% by avoiding 38 tonnes of carbon dioxide (González & García Navarro 2006). Dimoudi and Tompa
(2008) state that the embodied energy of an office building can represent from 13% to 19% of operational energy over a 50 year life of the project (Dimoudi, A. & Tompa, C. 2008). They also report the energy consumption and carbon dioxide emissions for two different office buildings, where the first building consumed 1.93 GJ/m² and provided 198 kg CO₂-e emissions /m² and the second building consumed 3.97 GJ/m² and purchased 289.4 kg CO₂-e /m². These authors also note that the embodied energy in structural materials (concrete and steel reinforcement) are the largest percentage of energy embodied in these buildings because the first building had 66.73% and the second building reached 59.57% of the total embodied energy (Dimoudi, A. & Tompa, C. 2008). The parameters responsible for variations in embodied energy data can be summarised into discrepancies in the system boundaries (Dixit et al. 2012; Hammond & Jones 2010; Lenzen 2000; Reap et al. 2008), methods of computing embodied energy (Joseph & Tretsiakova-McNally 2010; Lenzen 2000; Optis & Wild 2010), the geographic location of the study (Dixit et al. 2012; Optis & Wild 2010), the type of energy used (primary and delivered)(Dixit et al. 2010; Dixit et al. 2012), and the quality and source of data (Lenzen 2000; Menzies et al. 2007; Peereboom et al. 1998).

2.8.5 Calculating the embodied energy

Embodied energy is defined as the total energy required to construct a building, including the direct energy used in construction and assembly, as well as the indirect energy needed to manufacture the materials and building components. The energy content of materials refers to the energy used to extract raw materials, as well as manufacture and transport to the building site. The primary methods used to determine embodied energy are Input-Output economic based analysis, Process-
based analysis, and Hybrid analysis. These methods differ in how data about input energy is collected in the main materials production and administration process.

An Input-Output method of analysis could account for most of the direct energy and indirect energy by using economic data whereby money flows between different sectors of industry in the form of Input and Output tables, as applied by a national government. In other word, this method is transcribing economic flow into energy flows by applying average energy tariffs. For instance, Junnila and Horvath (2003) applied the Input-Output method to evaluate the life cycle of CO₂-e emissions embodied in a 5-storey concrete building, while Cho et al. (2012) used it to determine the life cycle of CO₂-e emissions associated with three steel buildings constructed from rigid-frame, braced-frame and outrigger structures, respectively. However, this method still suffers from problems such as differences in the economic data from country to country such as energy tariffs, product costs, and even how the sectors are grouped (Goggins et al. 2010). The Input-Output method can provide an industry wide environmental analysis but it cannot quantify a detailed and process specific analysis of CO₂-e emissions from material production (Gan et al. 2017; Kofoworola & Gheewala 2008).

The Process-based method considers building materials as the final products and then all the possible direct input energy works upstream of the main process and to deliver more accurate and reliable results. Process-based analysis is a widely used method because it leads to more accurate and reliable results (Crawford & Treloar 2003; Dixit et al. 2010), however, it is also deemed to be incomplete because some of the upstream processes are truncated or excluded due to the attributes needed to identify and quantify each product input, and small energy of the complex upstream process (Crawford & Treloar 2005). To calculate the energy embodied in a building, the quantities
of all the materials must be calculated and multiplied with the respective Process-based embodied energy intensities (Dixit 2017; Dixit et al. 2012; Rauf & Crawford 2015; Stephan & Stephan 2016). Several studies used Process-based assessment methods in their analysis to determine the embodied CO\textsubscript{2}-e emissions associated with materials such as wood, brick, masonry and low-medium strength concrete (Gan et al. 2017; Gustavsson et al. 2010; Scheuer et al. 2003). Nadoushani and Akbarnezhad (2015) applied a process-based life cycle assessment to determine the embodied CO\textsubscript{2}-e emissions of various materials in several mid-rise buildings with rigid frame and shear walls. Yan et al. (2010) also used a Process-based method to evaluate a 30-story concrete building by using the embodied CO\textsubscript{2}-e emissions coefficient for production, transportation, construction and waste disposal.

Because of the inherent problems with Input-Output analysis and Process-based, Hybrid methods of embodied energy analysis have been established. A Hybrid analysis unifies the benefits of two first methods to mitigate errors and limitations of Process-based and Input-Output analysis. This method of analysis commences with a Process-based analysis of accessible energy input data at the final production stage, and then shifts to the Input-Output base analysis when achieving reliable and consistent data are difficult due to the complexity of the upstream process. Hence, the Hybrid analysis method is categorised into Process-based Hybrid analysis and Input-Output Hybrid analysis (Suh et al. 2004; Treloar 1997).

Input-Output Hybrid analysis is based on the identification and extraction of a direct energy path from the Input-Output based method, as well as integrating Process-based data to prevent indirect effects. As Treloar (2003) states, Input-Output Hybrid analysis is considered as an appropriate method in the life cycle assessment of buildings (Langston & Langston 2008).
Process-based Hybrid analysis integrates Input-Output data to complex parts of upstream processes of material production to reduce the inherent problem with the Process-based method. The process-based Hybrid model is an appropriate method for analysing large atypical products, if all the inputs are drawn far enough back, however, complex materials and overestimated prices of products could raise problems for this method (Dixit et al. 2010). A review of these methods indicates that they all have strengths and limitations, but the Hybrid analysis is the preferred approach for embodied energy due to its systemic completeness and use of reliable data, if available (Crawford 2011; Crawford 2008; Lenzen & Crawford 2009; Majeau-Bettez et al. 2011; Rauf & Crawford 2015).

The system boundary of a Process-based Hybrid analysis or Hybrid material energy coefficients has the same limitations as a process analysis because many of the direct inputs to a process can be excluded (Lenzen & Dey 2000; Rauf & Crawford 2015). An Input-Out Hybrid analysis addresses the truncation issues associated with a process-based Hybrid analysis by using Input-Output data to fill in any gaps remained in the data (Rauf & Crawford 2015; Yu et al. 2017). An Input–Output based Hybrid analysis is more complete and less data and labour intensive (Rauf & Crawford 2015; Yu et al. 2017). The study of a residential building and other household products shows that embodied process analysis values can be up to 87% lower than equivalent Input-Output based hybrid analysis values (Crawford 2008); so, analytical methods have been developed to estimate the embodied energy and CO2-e emissions in building products. Section 2.10 summarises the databases and tools available to determine the embodied energy and CO2-e emissions in building products.
2.8.6 Operational energy

The operational energy consists of the energy used to maintain comfortable conditions and daily maintenance; basically, it’s the energy used for heating, cooling, hot water, lighting, and for running appliances and operating equipment. Operational energy varies according to the range of comfort required, the climatic conditions, and the function of the building. Operational energy over the lifetime of a project is expressed as the annual operating energy multiplied by the lifetime of the project.

The operational energy is generally greater than the embodied energy over the lifetime of a building (Torgal & Jalali 2011). Many studies suggest different passive and active technology to reduce the amount of operational energy (Kestner et al. 2010). With passive design, the amount and type of insulation in the external walls and roofs, the building’s orientation, the use of shading and glazing for windows, passive solar heating and thermal mass, contribute to improving the overall energy usage of a building (Kestner et al. 2010).

Wang et al. (2007) developed a framework which begins with climate data to state the design objectives, then defines the passive design alternatives based on building orientation, form, and the energy efficiency of building services (as shown in Figure 2-12).
Heating, cooling, ventilation, and the provision of hot water are generally responsible for most of the energy consumed in buildings (Karimpour et al. 2014; Pérez-Lombard et al. 2011). Space heating is often the highest share of the total operational energy; this amount of this energy can be calculated by subtracting the total heat loss from the free heat gain. The annual amount of energy consumed in office buildings varies between 100 to 1000 kWh per square metres depending on the type and use of office equipment, the climatic condition of the project, and the use of heating, ventilation, and air conditioning (HVAC) (Pitt&Sherry 2012). In Australia, a typical office building
from 1999 to 2012 shows that electricity is used for HVAC (43%), Lighting (26%) and equipment (20%), as shown in Figure 2-13 (Pitt&Sherry 2012).

![Figure 2-13 Offices (All), Electricity End Use Shares, 1999 – 2012 (Pitt&Sherry 2012)](image)

Data on the amount of natural gas used from 1999 to 2012 shows that space heating accounts for the majority of gas consumed (as shown in Figure 2-14).

![Figure 2-14 Offices (All), Share of Natural Gas End Use 1999 – 2012 (Pitt&Sherry 2012)](image)

2.9 Environmental impact of material selection

The previous section shows the environmental impact of buildings by considering embodied energy and operation over the lifetime of a building. The embodied energy shows the amount of energy consumed to extract, refine, process, transport and fabricate a material or product (including...
buildings), while the operational energy defines the energy consumed during the usage of a building. This section summarises the challenging section of the concrete as one of the most used construction materials, by focusing on the embodied carbon footprint (CO₂-e emissions) and thermal properties.

2.9.1 Embodied CO₂-e emissions

Concrete is the most widely used material in every type of construction due to its strength and durability. It is estimated that around 25 billion tons of concrete are produced globally each year. Unlike other construction materials, concrete has a lower environmental impact because its production and its ingredients do not require a great deal of energy (Marinković et al. 2014). The amount of CO₂-e emissions associated with the production of concrete and its relative impact is quite small, but due to the large consumption of natural resources and the waste generated, the overall negative environmental impact is quite significant. The production of cement as a key component of concrete has attracted much attention in life cycle assessments due to its energy-intensive production process which produces large amounts of CO₂-e emissions (Shen et al. 2015; Zhang et al. 2013). Due to the increasing sustainability concerns in the building and construction industry, concrete technology uses supplementary cementitious materials to replace the cement, that are generated as industrial waste or by-products; the most widely used are Granulated Blast Furnace Slag (GBFS), Fly ash, and Silica Fume (Abdalqader et al. 2016; Li et al. 2016). Hossain et al. (2018) summarised the impact of supplementary cementitious materials in concrete mix design and found that by selecting appropriate materials, the environmental impact can be reduced up to 38% compared to convention concrete (Hossain et al. 2018). A summary of the
methodological aspects associated with a life cycle analysis of concrete and concrete products is shown in Table 2-6.

**Table 2-6 A review of life cycle analysis on concrete and concrete product (adopted from (Hossain et al. 2018))**

<table>
<thead>
<tr>
<th>Reviewed Literature</th>
<th>Type of SCMs</th>
<th>Application</th>
<th>Country</th>
<th>Functional unit</th>
<th>System boundary</th>
<th>Life cycle inventory data</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Flower &amp; Sanjayan 2007)</td>
<td>FA, GBFS</td>
<td>Concrete</td>
<td>Australia</td>
<td>1 m³</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>(O’Brien et al. 2009)</td>
<td>FA</td>
<td>Concrete</td>
<td>Australia</td>
<td>1 m³</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>(Habert &amp; Roussel 2009)</td>
<td>FA, GBFS</td>
<td>Concrete</td>
<td>France</td>
<td>1 m³</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Chowdhury et al. 2010)</td>
<td>FA</td>
<td>Road construction</td>
<td>USA</td>
<td>1 kg</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>(Chen et al. 2010)</td>
<td>FA, GBFS</td>
<td>Comparison of SCMs with cement</td>
<td>France</td>
<td>1 kg</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>(Habert et al. 2011)</td>
<td>FA, GBFS</td>
<td>Concrete</td>
<td>France</td>
<td>1 m³</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>(Hajek et al. 2011)</td>
<td>SF</td>
<td>Concrete</td>
<td>Czech Republic</td>
<td>1 m³</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>(Van den Heede &amp; De Belie 2012)</td>
<td>FA, GBFS</td>
<td>Comparison: SCMs &amp; cement; different LCA methods</td>
<td>Belgium</td>
<td>1 kg</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>(Park et al. 2012)</td>
<td>FA, GBFS</td>
<td>Concrete</td>
<td>South Korea</td>
<td>1 m³</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>(Crossin 2012)</td>
<td>FA, GBFS</td>
<td>Concrete blend</td>
<td>Australia</td>
<td>1 m³</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>(Proks et al. 2013)</td>
<td>FA, GBFS</td>
<td>Concrete</td>
<td>Germany</td>
<td>1 m³</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>(Knoeri et al. 2013)</td>
<td>FA</td>
<td>Concrete</td>
<td>Switzerland</td>
<td>1 m³</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>(De Schepper et al. 2014)</td>
<td>FA</td>
<td>Concrete</td>
<td>Belgium</td>
<td>1 m³</td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>(Randl et al. 2014)</td>
<td>FA, GBFS</td>
<td>Concrete</td>
<td>Austria</td>
<td>1 m³</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>(Van den Heede &amp; De Belie 2014)</td>
<td>FA</td>
<td>Concrete</td>
<td>Belgium</td>
<td>1 m³</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>(Zhang et al. 2014)</td>
<td>FA</td>
<td>Concrete</td>
<td>Hong Kong</td>
<td>1 m³</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>(Blankenelaal et al. 2014)</td>
<td>FA, GBFS</td>
<td>Concrete</td>
<td>the Netherlands</td>
<td>1 m³</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>(Seto 2015)</td>
<td>FA</td>
<td>Concrete</td>
<td>Canada</td>
<td>1 m³</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>(Li et al. 2015)</td>
<td>FA</td>
<td>Concrete</td>
<td>China</td>
<td>1 m³</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>(Turk et al. 2015)</td>
<td>FA</td>
<td>Concrete</td>
<td>Slovenia</td>
<td>1 m³</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>(Saade et al. 2015)</td>
<td>GBFS</td>
<td>Cement</td>
<td>Brazil</td>
<td>1 t</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>(Anastasiou et al. 2015)</td>
<td>FA, GBFS</td>
<td>Concrete</td>
<td>Greece</td>
<td>1 km</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>(Celik et al. 2015)</td>
<td>FA, LP</td>
<td>Concrete</td>
<td>USA</td>
<td>1 m³</td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>(Crossin 2015)</td>
<td>GBFS</td>
<td>Concrete</td>
<td>Australia</td>
<td>1 m³</td>
<td></td>
<td>*</td>
</tr>
</tbody>
</table>
Another advantage of concrete is its high thermal mass which affects the thermal performance of a building. Constructions with a high thermal mass usually contain heavyweight materials such as concrete (normal weight) and typically result in indoor environments with relatively small variations in temperature (Zhu et al. 2009). The thermal mass is directly related to the mass of a building which is stored in floors, walls, ceilings and partitions, and the thermal storage capacity is affected by the surface area, thickness of the building’s component, and is also a function of the material used in the building (Hensen & Lamberts 2012). The primary factors affecting the thermal properties of the building materials are thermal conductivity, specific heat capacity, and the density of the material (Hensen & Lamberts 2012).
With concrete and concrete products, the thermal properties are influenced by the amount of cement paste, the aggregate and the presence of moisture (ACI122R 2014). Damdelen et al. (2014) experiments have shown that the GGBS content in concrete mixes provides the highest thermal admittance while concrete mixes with silica fumes have a similar thermal admittance value as Portland cement (Damdelen et al. 2014). Robati et al. (2016) also show that the type of aggregate affects the density and thermal conductivity, while replacing normal aggregate with lightweight aggregate reduces the density and thermal conductivity of concrete. Specific heat/heat capacity is another indicator of thermal inertia, but as highlighted in the ACI122R, the specific heat does not change across concrete with different densities (from 1280 to 2240 kg/m$^3$) (ACI122R 2014). Recent developments in concrete admixtures have led to the production of a novel Ultra-lightweight concrete (1,350 to 1,900 kg/m$^3$) with a much lower thermal conductivity than normal concrete (2,200 to 2,600 kg/m$^3$) (Marinkovic et al. 2010; Wu et al. 2015; Yun et al. 2013; Zhang & Poon 2015). Roberz et al. (2017) state that buildings with a high thermal mass require more time to heat up or cool down, which might lead to thermal discomfort and increase the heating and cooling load. However, there is some concern about higher sensitivity as the temperature of concrete fluctuates with a lower thermal conductivity (Ponechal & Staffenova 2017; Robati et al. 2017; Roberz et al. 2017). In response, Al-Sanea and Zedan (2011) point out that an adequate amount of thermal mass and types of materials are associated with the case study building, and this depends on many interrelated factors such as weather conditions, the occupancy pattern, internal heat gains, HVAC type, building orientation, fenestration and the shading system (Al-Sanea & Zedan 2011). The following section summarises the literature reviewed on the environmental life cycle assessment tools and databases.
2.10 Environmental LCA tools and databases

The sources of data for life cycle analysis can be classified in accordance with the different phases of manufacture, operation, and demolition. The possible source of data for the manufacturing phase of building materials can be found by considering the economic input and output table, process based or hybrid based, or even from literature by considering the quantities of materials used, the bills, and the average distance material is transported (Whitehead et al. 2014).

Evaluating the energy performance of buildings depends on factors related to local climate conditions. So, a possible source of data for the operational phase can be extracted from annual electricity usage and fuel consumption for heating purposes, household survey and energy simulation software (Cabeza et al. 2014). The total amount of energy used in a building over its lifespan can be estimated by a summation of all the energy consumed during all phases, some of which have been carried out to compare the features and capability of an energy simulation program (Crawley et al. 2008; Foucquier et al. 2013; Nguyen et al. 2014). Harish and Kumar (2016) reviewed the most used modelling methodologies that were developed and adopted to model the energy systems of buildings (Harish & Kumar 2016). EnergyPlus is a proven building performance simulation program tool in common practice in the Australian context (Asadi et al. 2012; Daly 2015; Ryan & Sanquist 2012; Yalcintas 2008), while DesignBuilder is a third-party graphical user interface for EnergyPlus that has been used in many studies in Australia (Chowdhury et al. 2008; Daly 2015; Rahman et al. 2010; Rahman et al. 2011). The source data for the demolition phase can be stated as operating the equipment and the average distance material is transported over the demolition time (Langston & Langston 2008).
Finally, a life cycle analysis estimates the impact that a building makes on the environment (Adalberth 1997). Table 2-7 summarises the data sources for life cycle energy analysis of a building at different phases.

**Table 2-7 Data sources for life cycle energy analysis**

<table>
<thead>
<tr>
<th>Life cycle phase</th>
<th>Activity</th>
<th>Source of Data</th>
</tr>
</thead>
</table>
| (a) Manufacturing                     | Building material production                  | • Manufacturing energy data of the building materials from literature, economic process analysis, input/output tables, hybrid analysis  
                                          |                                               | • Quantities estimated from building drawings, bill of materials and from interviews with building  
                                          |                                               | • Designer, contractor/owner                  |
|                                       | Transport                                      | • Average distances for material transport  
                                          |                                               | • Energy data for transport operations       |
|                                       | Building construction including refurbishment | • Energy use from site visit                                                      |
| (b) Use                               | Use of electricity and fuels for heating, sanitary, water and lighting | • Simulation software (EnergyPlus, VisualDOE, e-QUEST, DesignBuilder, ENORM, TRNSYS, Ecotect, SunCode, etc., annual electricity bills, household survey on energy use, Inventory data for fuel production, Electricity mix data. |
| (C) Demolition                        | Building demolition                            | • Demolition operations and quantities from specific measured data  
                                          |                                               | • Use of equipment and explosives from database |
|                                       | Transport                                      | • Average distances for material transport  
                                          |                                               | • Energy data for transport operations       |
|                                       | Recycling                                      | • Specific measurement data                                                          |
| Life cycle energy and embodied CO₂-e emissions | Total energy use and embodied CO₂-e emissions of the building in its life cycle | • Phase (a+b+C)                                                                        |
| Life cycle assessment                 | Life cycle material and energy flow estimation | • Greenhouse effect or global warming, ozone depletion, acidification, eutrophication, photochemical smog, etc. estimated using software: SimaPro, ECOBAT, LEGEP, BEES, ATHENA, etc. |
|                                       | Impact assessment that building makes on the environment | • Phase (a+b+C)                                                                        |
For the purpose of life cycle analysis, there are various inventory databases and software tools which are classified as product assessment tools, whole of building decision support tools and whole of building assessment system framework. Within the product assessment tool, the building products are considered to be the smallest part of any analysis. These tools compare and evaluate building products across each other, and as such, provide a platform such as Building for Environmental and Economic Sustainability (BEES) (Cabeza et al. 2014).

A building assembly tool is a group of interdependent components that create a specific system in a building. This means that all of the materials and elements needed to build a wall system can be evaluated by a building assembly tool that will analyse the effects that each alternative will have on the environment (Cabeza et al. 2014). There is a wider scope of tools in the product assembly, such as ATHENA eco calculator tools (Cabeza et al. 2014).

Whole of building asset tools evaluate the environmental effects of a building as a unique system by considering all the systems and assemblies. These tools can compare the design alternatives which are very useful in early stage of a project design. For example, the ATHENA Impact Estimator considers the whole building as an input by considering the building geometry and assemblies. The final results of these tools are amassed for the whole building and presented as the environmental impact due to variety of life cycle phases and the specific impact made by the building (Cabeza et al. 2014). The following sections provide a brief description of the inventory databases available.
2.10.1 ICE (Hammond et al. 2011)

In England, Hammond and Jones developed a database to determine the embodied energy and embodied carbon of a large number of building materials (Hammond et al. 2011). This database includes data that fulfils the ISO standard requirements and it has been used to release the Inventory of Carbon and Energy (ICE) which covers the boundary for each material, from the extraction of raw materials, the process and manufacture of product to dispatch at the company “cradle to gate” (Hammond et al. 2011; Hammond & Jones 2008; Lamnatou et al. 2014).

2.10.2 Envest 2 (Whitehead et al. 2014)

Envest 2 was established by the Building Research Establishment (BRE) in the UK to allow users to access the environmental impact as well as a comparison across each other by considering whole life costing of construction materials and the energy consumed during the operational phase of buildings. Although this tool considers the lifetime of project by including the energy consumed in heating, cooling, and daily operating, it does not have enough data to cover the embodied energy of building components (Watson & Jones 2005; Whitehead et al. 2014).

2.10.3 Ecoinvent (Takano et al. 2014)

In Switzerland, the Ecoinvent database was developed in late 2000 to supply a life cycle inventory data that includes all the economic activities at a unit process level (Takano et al. 2014). The last version of this Ecoinvent database (version 3.3) considers datasets at the unit process level where they can be linked to different system models. The philosophy behind this method is that the primary production of materials is only assigned to primary materials, while products are classified into one of three categories (ordinary by-product, recyclable material, and waste) which are based
on the level of products, not on individual activities (Ecoinvent 2013; Frischknecht et al. 2005; Frischknecht et al. 2007).

2.10.4 Athena (Tharumarajah & Grant 2006)

In the USA, the Athena life cycle inventory database was created by the National Renewable Energy Laboratory and the Athena institute. This database provides individual gate-to-gate, cradle to gate, and cradle to grave boundaries to account for the amount of energy and materials flowing into and out of the environment. The resulting boundaries are associated with activities for producing materials as well as manufacturing and assembling products within the United States (Rebitzer et al. 2004; Tharumarajah & Grant 2006).

2.10.5 BEES (Suh et al. 2014)

The national Institution of Standard and Technology developed the BEES software to measure the environmental performance of building products using a life cycle assessment. This software provides a product to product comparison in terms of environmental and economic performance (Suh et al. 2014). BEES only includes materials which have significant cost, energy, or weight. This tool covers 280 building products and aims to assist in the selection of potentially green and cost effective products (Cabeza et al. 2014; Suh et al. 2014). BEES is primary useful for analysing products during the manufacturing process because it does have some limitations when used to analyse building processes and building materials such as the use and maintenance of insulation (Forsberg & von Malmborg 2004; Haapio & Viitaniemi 2008).
2.10.6  ELCD (Finnveden et al. 2009)

The European reference Life Cycle Database (ELCD) consists of Life Cycle Inventory (LCI) data from front-running EU-level business associations and additional sources for key materials, energy carriers, transport, and waste management (ELCD 2007; Finnveden et al. 2009).

2.10.7  GaBi (Takano et al. 2014)

The GaBi database is a product system assessment tool that first appeared in 1992 from PE International as a German company. This database provides information on the life cycle inventory for commercial purposes and also compares principal life cycle inventory datasets collected from industries, associations and public sections worldwide (Takano et al. 2014). The GaBi tool uses an integrated product database developed through technical literature and industry review. This database has been used as a reference database in forms of life cycle assessment calculation in the context of the German building certification system (Takano et al. 2014). However, the use of phase impacts have not yet been addressed adequately (Cabeza et al. 2013).

2.10.8  AusLCI (Islam, Hamidul et al. 2015)

The Australian National Life Cycle Inventory Database (AusLCI) is a major initiative currently being delivered by the Australian Life Cycle Assessment Society (Islam, Hamidul et al. 2015). The development of AusLCI was requested by stakeholders from industry, government, and academia in order to deliver a methodology for applying ISO 14040 measurements in Australia. AusLCI assists with providing LCA for a whole life of product as well as benchmarks for eco labelling. The results of AusLCI data cover all the main impact areas by considering the use of land, the reduction of water, eutrophication, human toxicity, eco toxicity, ozone depletion, photo-chemical
ozone formation and global warming (Rebitzer et al. 2004; Renouf et al. 2015; Tharumarajah & Grant 2006).

2.10.9 eTool (eTool 2014)

This online tool was developed in Australia as life cycle assessment tool called eTool; it uses a life cycle analytical method to include the energy embodied over the total design life of a building. This eTool complies with ISO 14044, ISO14040 and EN 15978 (Iyer-Raniga et al. 2014), and the default materials and energy are based on an Australian life cycle inventory database. It also covers embodied energy from cradle to gate by considering all the energy used to extract the raw materials and process them into useable building products. The eTool life cycle boundary is shown in Figure 2-15 (eTool 2014).

Figure 2-15 eTool boundary system(eTool 2014)
2.10.10 Crawford (Crawford 2011)

In terms of the inventory energy database in Australia, Treloar and Crawford (2010) proposed an embodied energy coefficient for selected building materials by considering all the production processes from the extraction of raw materials, transporting to the company, and from manufacturing and finishing the material (cradle to gate). Treloar and Crawford (2010) used an energy based Input-Output model developed by Professor Manfred Lenzen at the University of Sydney, as well as Australian process data compiled by Grant (2002). The energy used in construction, operation, maintenance, refurbishment, demolition, and reuse and recycling is excluded from this study (Crawford 2011; Crawford 2008; Stephan 2013).

Table 2-8 is a summary of the national and international inventory databases, industry data report, and available software.

Table 2-8 Summarises the basic information about each database and tools (adopted from (De Wolf et al. 2017))

<table>
<thead>
<tr>
<th>Industry data reports</th>
<th>EEC</th>
<th>ECC</th>
<th>LCA</th>
<th>Method</th>
<th>Boundaries</th>
<th>Region</th>
<th>Free</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inventory of Carbon and Energy (ICE)</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>Literature</td>
<td>Cradle to gate</td>
<td>UK</td>
<td>✓</td>
</tr>
<tr>
<td>Structure and Carbon (Carbon working group)</td>
<td>✓</td>
<td></td>
<td></td>
<td>Engineering</td>
<td>Cradle to gate</td>
<td>US</td>
<td>✓</td>
</tr>
<tr>
<td>Hutchins UK Building Blackbook</td>
<td>✓</td>
<td></td>
<td></td>
<td>Economic I/O LCA</td>
<td>Cradle to gate</td>
<td>UK</td>
<td></td>
</tr>
<tr>
<td>WBCSD on cement</td>
<td>✓</td>
<td></td>
<td></td>
<td>Manufacturing</td>
<td>Cradle to gate</td>
<td>World</td>
<td>✓</td>
</tr>
<tr>
<td>NRMCA on concrete</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>Manufacturing</td>
<td>Cradle to gate</td>
<td>US</td>
<td></td>
</tr>
<tr>
<td>World Steel</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>Manufacturing</td>
<td>Cradle to gate</td>
<td>World</td>
<td></td>
</tr>
<tr>
<td>CORRIM on timber</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>Manufacturing</td>
<td>Cradle to gate</td>
<td>US</td>
<td></td>
</tr>
<tr>
<td>Software and tools</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon Calculator Environmental Agency</td>
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<td></td>
<td></td>
<td>Economic I/O LCA</td>
<td>Cradle to gate</td>
<td>UK</td>
<td>✓</td>
</tr>
<tr>
<td>BEES</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>Economic I/O LCA</td>
<td>Cradle to gate</td>
<td>US</td>
<td>✓</td>
</tr>
<tr>
<td>Athena Sustainable Materials (North America)</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>Process LCA</td>
<td>Cradle to gate/grave</td>
<td>N. America</td>
<td>✓</td>
</tr>
<tr>
<td>Tool/Database</td>
<td>✓</td>
<td>✓</td>
<td>Process LCA</td>
<td>Cradle to gate/grave</td>
<td>Location</td>
<td></td>
<td></td>
</tr>
<tr>
<td>---------------------------------------</td>
<td>-----</td>
<td>-----</td>
<td>-------------</td>
<td>----------------------</td>
<td>-----------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CCaLC Tool</td>
<td>✓</td>
<td>✓</td>
<td>Process LCA</td>
<td>Cradle to gate</td>
<td>UK</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GaBi</td>
<td>✓</td>
<td>✓</td>
<td>Process LCA</td>
<td>Cradle to grave</td>
<td>Germany</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GEMIS</td>
<td>✓</td>
<td>✓</td>
<td>Process LCA</td>
<td>Cradle to gate</td>
<td>Germany</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LEGEAP Software GmbH</td>
<td>✓</td>
<td>✓</td>
<td>Process LCA</td>
<td>Cradle to gate</td>
<td>Germany</td>
<td></td>
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</tr>
<tr>
<td>LTE OGIP</td>
<td>✓</td>
<td>✓</td>
<td>Economic I/O* LCA</td>
<td>Cradle to grave</td>
<td>Germany</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sankey Editor</td>
<td>✓</td>
<td>✓</td>
<td>Process LCA</td>
<td>Cradle to grave</td>
<td>Germany</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Umberto</td>
<td>✓</td>
<td>✓</td>
<td>Process LCA</td>
<td>Cradle to grave</td>
<td>Germany</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SimaPro &amp; OpenLCA</td>
<td>✓</td>
<td>✓</td>
<td>Process LCA</td>
<td>Cradle to grave</td>
<td>Netherlands</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OpenLCA</td>
<td>✓</td>
<td>✓</td>
<td>Process LCA</td>
<td>Cradle to grave</td>
<td>Netherlands</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EQUER and novaEQUER</td>
<td>✓</td>
<td>✓</td>
<td>Process LCA</td>
<td>Cradle to grave</td>
<td>France</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Qantis suite</td>
<td>✓</td>
<td>✓</td>
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**Databases**

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<td>✓</td>
<td>EPD</td>
<td>Cradle to gate</td>
<td>NZ</td>
</tr>
</tbody>
</table>

EEC: Embodied Energy Coefficients; ECC: Embodied Carbon Coefficients; LCA: Life Cycle Assessments; Environmental Product Declaration (EPD); Life Cycle Inventory Analysis (LCIA); Input/Output (I/O)
2.11 Life cycle uncertainty analysis

The use of sustainable building materials to minimise the environmental impact and to improve the energy performance has been increasingly at the centre of attention. A comprehensive life cycle approach must consider how material section impacts the entire life of building, including the extraction of raw materials, manufacturing processes, transportation to the construction site, construction processes, the operational phase, and the end of life recycling and potential for reuse (Ding 2014). However, applying life cycle procedures to buildings may not be straightforward because they can present difficulties and uncertainties at different stages of a building’s life.

In the operational stage building, energy models have been used to predict the average energy consumption of a building (Faggianelli et al. 2017). Quantifying the uncertainties for operational energy has been the topic of a large number of studies (Coakley et al. 2014; Daly et al. 2014; Eisenhower et al. 2012; Jain et al. 2015; Tian 2013); so, this will not be discussed any further in this thesis. However, little is known about uncertainties associated with the selection of building materials over the life cycle of embodied CO2-e emissions of buildings. Several studies have revealed the growing significance of embodied emissions and have shown its relationship to the lifecycle carbon emissions of buildings (Ayaz & Yang 2009; Dixit et al. 2010; Ibn-Mohammed et al. 2013; Lee & White 2008).

Uncertainty analysis is a useful tool to quantify the risk associated with variations in input parameters and their influence on the overall life cycle environmental impacts (Hong et al. 2016). Several studies state that the lack of comprehensive production records and differences in manufacturing process result in many variations in the CO2-e emissions coefficient and the embodied energy coefficient factor (Ozoemena et al. 2017; Robati et al. 2016). For instance, Robati
et al. (2016) identifies some inconsistencies in the calculation of embodied CO₂-e emissions across the different databases. This is attributed to variations in embodied CO₂-e emissions coefficients and a lack of in-depth consideration of the detailed properties of each individual concrete mix design (Robati et al. 2016).

Several studies proposed stochastic modelling and interval calculation as a reliable and accepted method for uncertainty analysis in life cycle assessment (Ozoemena et al. 2017; Wang & Shen 2013). For instance, Blengini and Di Carlo (2010) used Monte Carlo analysis to understand the reliability of life cycle assessment for a case study building. They considered the uncertainties associated with the quantity of materials (production and maintenance), transport distance, and energy consumption for heating, cooling, and domestic hot water and cooking. A Monte Carlo analysis using behavioural modelling of data uncertainty through probability distributions can be used to define the optimal solutions for a project. Another study acknowledged the impacts of uncertainties in materials and the life span of buildings over the life cycle performance of buildings (Aktas & Bilec 2012). Aktas and Bilec (2012) showed that selecting a random service life for building materials and systems leads to a significant variation in the results of a life cycle assessment (Aktas & Bilec 2012). Also, Leung et al. (2015) showed an ongoing trend to improve methods for predicting uncertainties and modelling (Leung et al. 2015). Their study is based on 134 journal articles of uncertainty analysis methods associated with the environmental impact of buildings (Leung et al. 2015). Despite all the previous studies, there is still a lack of work aimed at quantifying uncertainties associated with structural design and construction forms.
2.12 Structural design procedure:

Concrete flooring systems provide a designer with a variety of alternative floor systems for a specific building. AS3600 (2009) provides the minimum criteria for the design of concrete structures in Australia. The structural systems of mid to high-rise building are based on considerations that regularly address the efficiency of structural systems in terms of unit structural materials (Ali & Moon 2007; Cho et al. 2004); however, the unit structural quantity cannot reflect the complexities of mid to high rise buildings because as different structural materials are integrated, their costs and variations with the speed of construction must be considered too.

2.12.1 Structural system

Ali and Moon (2007) classified the structural systems of tall buildings into interior and exterior structures and this is based on how the components for the primary lateral load resisting system will be distributed in the building. The interior is assigned to the building when the main lateral loading resisting system is located inside, and an exterior structure is given to the building when the main part of lateral loading resisting system is located at the primate of the building. Interior structures are suggested for buildings up to 20 storeys and they have two main structural components: moment resisting frames and shear trusses/ shear walls, while exterior structures are for buildings of up to 160 stories and they typically consist of a tube in the core of the structures. Figures 2-16 and 2-17 show the concept of each system diagrammatically.
Figure 2-16 Interior structures (Ali & Moon 2007)
2.12.2 Floor system

A multi-disciplinary approach to selecting building components has been investigated. For instance, Takano et al. (2014) demonstrated the impact of selected building materials on embodied CO₂-e emissions and on the building cost in a Finish context, as the authors studied three building component categories—the structural frame, the inner components (insulation and sheathing), and the surface components (exterior cladding and flooring). They found that the materials selected influenced the embodied CO₂-e emissions and cost of the building (Takano et al. 2014). The selection of a concrete structural system is based on several factors specified by Australian Building Codes Board (ABCB 2015).
The ABCB (2015) provides a simplified and uniform set of regulations designed to establish essential construction standards for structural adequacy, fire resistance, public health and general amenity. The technical requirements of this code refer to AS3600 (2009) and other standards such as AS/NZ1170.0 (2002). There are several concrete floor systems that a designer can select and are economical and technically-satisfactory solutions. Concrete floor systems are generally reinforced using steel reinforcement, fabric, or high-strength strands that are pre-stressed. Pre-stressing concrete with a straight or a draped cable stabilises the applied loads by the uplift force and this limits how far the floor component can deflect. This is very beneficial for long-span floors because it removes the need to camber the formwork or to provide deeper reinforced concrete sections. With all concrete slab systems, careful attention should be given to shrinkage and shortening due to prestressing because both processes generate large forces in a floor system constrained by stiff columns or walls (Warner et al. 2010). Figure 2-18 summarise floor systems with regard to the length of their spans.
<table>
<thead>
<tr>
<th>Floor system</th>
<th>Comparative span (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat plate</td>
<td></td>
</tr>
<tr>
<td>Single span</td>
<td></td>
</tr>
<tr>
<td>Reinforced</td>
<td></td>
</tr>
<tr>
<td>Prestressed</td>
<td></td>
</tr>
<tr>
<td>Multi-span</td>
<td></td>
</tr>
<tr>
<td>Reinforced</td>
<td></td>
</tr>
<tr>
<td>Prestressed</td>
<td></td>
</tr>
<tr>
<td>Flat slab</td>
<td></td>
</tr>
<tr>
<td>Multi-span</td>
<td></td>
</tr>
<tr>
<td>Reinforced</td>
<td></td>
</tr>
<tr>
<td>Ribbed slab</td>
<td></td>
</tr>
<tr>
<td>Single span</td>
<td></td>
</tr>
<tr>
<td>Reinforced</td>
<td></td>
</tr>
<tr>
<td>Multi-span</td>
<td></td>
</tr>
<tr>
<td>Reinforced</td>
<td></td>
</tr>
<tr>
<td>Band beam and slab</td>
<td></td>
</tr>
<tr>
<td>Single span</td>
<td></td>
</tr>
<tr>
<td>Reinforced</td>
<td></td>
</tr>
<tr>
<td>Band beams at 8.4 m</td>
<td></td>
</tr>
<tr>
<td>Single span</td>
<td></td>
</tr>
<tr>
<td>Prestressed</td>
<td></td>
</tr>
<tr>
<td>Multi-span</td>
<td></td>
</tr>
<tr>
<td>Reinforced</td>
<td></td>
</tr>
<tr>
<td>Prestressed</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2-18 floor systems (CCAA 2003; Warner et al. 2010)
2.13 Summary

The literature shows the role played by structural engineers in the sustainable design of buildings. The key strategies and parameters associated with sustainable structural design strategies have been reviewed together with a detailed consideration of current international codes and specifications; the results highlight the main strategies and parameters which could affect the life cycle impacts of buildings. Various aspects of sustainable design and construction of buildings have been considered by researchers to minimise the environmental impact of structural design, but most focused on minimising the energy and resources consumed by buildings. Figure 2-19 provides the interactions between the key areas of knowledge reviewed.
Figure 2-19 Interaction between key areas of knowledge reviewed
There are noteworthy gaps in the field of sustainable structural design; one of the key challenges in the sustainable structural design of buildings is to improve their lifetime energy efficiencies and reduce their CO₂-e emissions impacts. Moreover, inconsistencies in estimating the CO₂-e emissions impact raises the need to address uncertainties associated with CO₂-e emissions impact made by different construction forms and concrete materials. The reviewed literature points out that structural engineers often overlook the influence that construction form and materials has on the thermal comfort and energy performance of a building, and not enough attention has been made to integrate the building and environmental costs into the decision making process. Chapter 3 presents a research methodology designed to meet the current study objectives and also cover those aforementioned knowledge gaps in the sustainable structural design of buildings.
Chapter 3

Research design

3.1 Introduction

Chapter 2 was a review of the relevant literature, and the contextual factors necessary for designing buildings with sustainable structures. The low carbon structure is linked to a reduction in their environmental impact resulting from the production of building materials, construction activities, maintenance and operational phases, and end of life processes. This Chapter proposes a methodology to integrate the lifetime of CO$_2$-e emissions, and the structural and economic aspects of a building structure over its intended life cycle.

To evaluate the environmental aspects of alternative structural designs, a Life Cycle Assessment (LCA) methodology is adopted because it has been used extensively to address environmental impact in the manufacturing and construction sectors (Ding 2014). The LCA in this study is used to quantify the carbon emissions associated with different design alternatives. The structural performance of buildings is also considered using the limit state method in the design process (AS3600 2009). The limit state design is a method used to design a structure by considering all actions likely to occur during its design life. The last step of this research methodology will combine the results obtained from a lifetime CO$_2$-e emissions study and structural design and express them as a single economic value. The structural and environmental costs are presented in the form of monetary units because they also represent the final outcomes from the sustainable parameters. The research methodology of this thesis is shown in Figure 3-1.
Figure 3-1 Overview of the methodology in this study
3.2 Overview of this methodology

This study uses a benchmarking design against which structural design alternatives can be compared in terms of their performance and environmental impact. The benchmarking system in this study is used to examine different climate zones in Australia, as well as different structural materials and methods of construction. This is carried out using a simulation model from a reference building as a base model and a sensitivity analysis. This comparative analysis is then presented in terms of lifetime energy and thermal performance as well as the life cycle cost and life cycle carbon emissions across design alternatives. This study then recommends ways to enhance the sustainable structural designs of buildings.

3.3 Benchmark building

Benchmarking aims to identify the right action where great savings can be made (Bosteels et al. 2010). This refers to evaluating building energy efficiency by comparisons with standards or established energy benchmarks. This study examines the potential CO2-e emissions associated with the concrete structure by using a benchmarking method to compare and quantify how construction forms and concrete alternatives affect the lifetime impacts of a building in Australia.

A typical 15-storey office building is used because it is one of the four benchmarking buildings proposed by the National standard Organization (NSDO) in Australia (NS11401.0 2014). This benchmark building will be used to simulate the carbon emissions, energy performance, and the cost of a building in Australia.

As mentioned in section 1.4.1, National Standards Development Organisation (NSDO) is a non-profit company which developed a principal standard NS11401.0 (NS11401.0
in early 2014 to specify the requirements for assessing and declaring the comparative environmental impact of building products and systems in Australia (NS11401.0 2014).

The system for constructing the proposed office building (reference building) is a typical high rise concrete structure in Australia (NS11401.1 2014); it has a square plan shape and a total floor area of 1000 m$^2$ metres, with an average 3.30 m height per storey, as shown in Table 3-1.

**Table 3-1 Benchmark building features**

<table>
<thead>
<tr>
<th>Building features</th>
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</thead>
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<tr>
<td>Basement dimensions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of Stories</td>
<td>-</td>
<td>15</td>
</tr>
<tr>
<td>Average elevation per floor</td>
<td>m</td>
<td>3.3</td>
</tr>
<tr>
<td>Total floor Area (including parking, Stairs &amp; Verandas)</td>
<td>m$^2$</td>
<td>15,000</td>
</tr>
<tr>
<td>Total habitable area (external dimensions)</td>
<td>m$^2$</td>
<td>8,807.1</td>
</tr>
<tr>
<td>No of floors above ground level</td>
<td>---</td>
<td>11</td>
</tr>
<tr>
<td>No of rooms</td>
<td>-</td>
<td>176</td>
</tr>
</tbody>
</table>

The building has two parts; the first three storeys are underground parking and storage areas, and the remaining twelve storeys are office areas. This building has a concrete frame structure with concrete columns and slabs, as well as precast concrete walls. The exterior sides of this building are shielded by non-opening windows. The square plan shape is designed as 31.62×31.62 m and there are doors on all four sides of the ground floor, as shown in Figure 3-2 and Figure 3-3.
3.4 Structural design parameters

As highlighted in sections 1.4 and 2.9, developments in concrete technology now offer a concrete mix with lower embodied CO₂-e emissions and lower thermal conductivity. It was shown that the appropriate choice of construction and building materials can potentially reduce the life cycle energy of buildings (section 2.9). The flooring of structural systems is a critical part of a building in terms of the CO₂-e emissions (section 2.12) and thermal performance (section 2.9).

As such in this study two aspects of structural design are examined over the whole life cycle of a building: floor systems (slab thickness) in different systems of construction, and different types of concrete (low density and high density).

A structural analysis is used to verify that the proposed building is a building design which could be used in practice for the purpose of this thesis. Based on the categories
in section 2.12.1, the structure of this building is designed with moment resisting frames and shear walls. The structural analysis first considered Flat plate as a floor system with a conventional column arrangement (5.27m) (NS11401.1 2014); based on the literature reviewed (section 2.12.2), the proposed building was then analysed and designed for different floor systems to cover a wider range of designs. For the alternative designs, the floor system is designed for slabs from 185 mm to 260 mm thick, depending on the type of floor systems. These flooring systems consist of the following:

- A post tensioned slab
- A Waffle slab
- A flat slab with a drop panel

Two types of concrete are used as the main structural materials; normal weight and Ultra-lightweight. Normal weight concrete has a density between 2,400 to 2,500 kg/m$^3$ and Ultra-lightweight concrete has a density lower than 1400 kg/m$^3$. Detailed information about those types of concrete is provided in Chapters 4, 6 and 7, and the structural design alternatives are summarised and shown in Figure 3-4.
3.5 Structural analysis and design method

In terms of structural analysis and design, a detailed concrete structure design is considered by following the Australian Standards Concrete structures (AS3600 2009). Two main aspects of this code, i.e., the strength and serviceability, were taken into the account during the structural design of this building. An overview of the method used for structural analysis is shown in Figure 3-5.
In this study the amount of live load came from the Australian and New Zealand standard for imposed actions (AS/NZ1170.0 2002). The live loads for office storage, parking, and work rooms are 5kPa and 3 kPa, respectively. The dead load for the concrete members was obtained by multiplying the volume of the member with the unit weight of concrete. Wind loads on the building were determined in accordance with the Australian and New Zealand standard wind actions (AS/NZ1170.2 2011). The magnitude of wind pressure on the structure was calculated based on height above ground, size, importance, and location. The importance level of the building is level 3, due to the consequences of failure based on the expected high rate of occupancy and use AS 1170.2002. For ultimate limit states and serviceability, the annual probability
 exceedance came from AS 1170.2.2002, Table 3.1, for designed working life of 50 years in a cyclic zone in Australia. To calculate the wind load, Zone D is used to ensure there is enough strength in the structure as well as validating the potential of constructing the building in other zones. For the loading conditions, a combination of actions is used to check the serviceability and strength of the building in accordance with clause 4.2.1 and 4.2.2 of the AS1170.2002, as shown in Table 3-2. The Computer Aid Design (CAD) package Etabs, Safe and a Microsoft Excel spreadsheet are used to verify the minimum requirements of the concrete design code. Details of the structural analysis and design are shown in Appendix B.

### Table 3-2 Loading conditions for designing the building

<table>
<thead>
<tr>
<th>Loading conditions</th>
<th>Type of load</th>
<th>Load (kPa)</th>
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<tr>
<td>Live load-Office storage and parking area</td>
<td>Dead Load</td>
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<td>Live load-Work rooms</td>
<td>Ultimate limit states</td>
<td>6.6</td>
</tr>
<tr>
<td></td>
<td>Serviceability limit states</td>
<td>5.4</td>
</tr>
<tr>
<td>Wind Load- Windward</td>
<td>Ultimate limit states</td>
<td>4.1</td>
</tr>
<tr>
<td></td>
<td>Serviceability limit states</td>
<td>3.4</td>
</tr>
<tr>
<td>Wind Load- Lee ward</td>
<td>Ultimate limit states</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>Serviceability limit states</td>
<td>1.1</td>
</tr>
<tr>
<td>Wind Load- Side wall</td>
<td>Ultimate limit states</td>
<td>1.3</td>
</tr>
<tr>
<td>Load combinations for Ultimate states design</td>
<td>Load combinations for serviceability states design</td>
<td></td>
</tr>
<tr>
<td>1.35G</td>
<td>G+ Ψl Q</td>
<td></td>
</tr>
<tr>
<td>1.25G+1.5Q</td>
<td>G+ Ψs Q</td>
<td></td>
</tr>
<tr>
<td>1.25G+1.5ΨlQ</td>
<td>G+ ΨsQ + Ws</td>
<td></td>
</tr>
<tr>
<td>1.2G+Wu+ΨcQ</td>
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<td></td>
</tr>
<tr>
<td>0.9G+Wu</td>
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<td></td>
</tr>
</tbody>
</table>

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

An environmental assessment method is used to estimate and quantify the potential environmental impact of different structural systems over the lifetime of the benchmark building. A life cycle environmental analysis of the building is divided into the following five phases: production, construction, use, end of life, and beyond life (as shown in Figure 3-6) (Moncaster & Symons 2013).

![Life cycle environmental impact analysis diagram](image)

**Figure 3-6 Building Life cycle**

The production and construction phases considered the extraction of raw materials, manufacturing, processing, and transportation to site; this is often called the “cradle to site” portion. The use phase considers the energy required to operate the building over its lifetime, while the end of life phase assumes the total estimated energy consumed at the end of life; beyond life represents the benefits and loads of components for reuse,
materials for recycling, and energy recovery for future use. The last stage of life cycle assessment (beyond life) is excluded from the scope of this study.

3.7 Life cycle environmental assessment approach

A life cycle environmental analysis assesses the lifetime building GHG emissions associated with the energy inputs; this concept can be used to illustrate the lifetime benefits of strategies design to minimise the GHG emissions (CO\(_2\)-e emissions) of buildings (Cabeza et al. 2014). The boundary of this system categorises the embodied CO\(_2\)-e emissions at the initial stage, operational stage, and end of life stage of buildings. The initial embodied CO\(_2\)-e emissions considers the impact of CO\(_2\)-e emissions as a result of the extraction of raw materials to the manufacturing processes, and from transportation to the construction site and construction activities. The operational phase accounts for the energy consumption and material replacement during the lifetime of the building, while the end of life provides information about embodied CO\(_2\)-e emissions associated with the demolition, transportation, and landfilled at the end of building life.

Information about embodied CO\(_2\)-e emissions associated with different concrete was extracted from several published outputs to address the lack of information on CO\(_2\)-e emissions of different concrete components in Australia (as shown in Table 4-2). The boundary of this system for calculating the total embodied CO\(_2\)-e emissions is shown in Figure 4-2. This study considered the embodied CO\(_2\)-e emissions associated with concrete and concrete materials from cradle to gate. This study includes every step from the extraction of raw materials, transport to the concrete plant, mixing, and the production of concrete by considering the energy consumed (Diesel fuel, LPG fuel and
electricity). The process of transportation and placement of concrete was excluded from this study. Table 4-3 summarises the final embodied CO₂-e emissions coefficients that are related to individual concrete components based on Australian data.

For the purpose of comparison, the results of embodied CO₂-e emissions associated with various types of concrete were compared against six publicly available inventory databases and guidelines that are commonly used in Australia:

- ICE (Hammond et al. 2011),
- Crawford (Crawford 2011),
- Alcorn (Alcorn 2003),
- eTool (eTool 2014),
- BPIC (BPIC 2014)
- AusLCI (AusLCI 2016)

The carbon dioxide (CO₂-e emissions) associated with the operational phase is estimated based on the energy used by the benchmark building. The building energy simulation software DesignBuilder is used to determine how different structural systems perform based on the ongoing energy consumption of a building (section 2.10). As section 2.10 shows, DesignBuilder is a user interface for the EnergyPlus dynamic thermal simulation engine; this software requires hourly weather files (based on epw standard format) while the required inputs for equipment and occupancy heat gaining and schedules are extracted from (NS11401.1 2014) and ABCB (2015).

Detailed information about the assumption and building properties are shown in section 6.3.1 and section 6.3.4. The results of operational energy are presented in terms
of the total energy used as well as the energy loads which are dominated by cooling energy across different design alternatives (Robati et al. 2017). The total energy demand of the building across different Australian climate zones was multiplied by the Australian national emissions factor in 2015 that was proposed by the Australian National Greenhouse Accounts (DEE 2016; DEE 2016), and then converted to CO₂-e emissions values (more information is provided in section 7.33). The embodied CO₂-e emissions associated with construction work, transportation, and final demolition at the end of life are estimated at a level of about 1% (Ruuska & Häkkinen 2015; Sartori & Hestnes 2007).

The mean distance from the manufacturing companies to the site (central business district for each city) is measured using the Google map tools (Poinssot et al. 2014). The five major cities are Sydney, Melbourne, Brisbane, Canberra and Darwin. The following table (Table 3-3) summarises all the steps involved in a life cycle environmental assessment and the available tools used in this thesis.
### Table 3-3 Life cycle assessment procedure

<table>
<thead>
<tr>
<th>Life cycle phase</th>
<th>Activity</th>
<th>Source of Data and method used</th>
<th>Tools for this study</th>
<th>Verification method</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Pre-use (Manufacturing)</td>
<td>Building material production</td>
<td>Manufacturing embodied CO$_2$-e emissions data for the building materials from literature and publicly available databases, as shown in Chapters 4 (4.5) and Chapter 5 (5.4).</td>
<td>Extracted initial coefficient from several published Australian outputs (for concrete); Excel spreadsheet for analysis.</td>
<td>Compare against 5 publicly available databases in Australia and an overseas one, including etool; ICE; Alcorn; Crawford; BPIC; AusLCI</td>
</tr>
<tr>
<td></td>
<td>Transport</td>
<td>Average distances for material transport by considering central business district; Available literature data about CO$_2$-e emissions for transport (Shown in Chapter 5.4).</td>
<td></td>
<td>Statistical analysis tools (JMP) and Excel spreadsheet</td>
</tr>
<tr>
<td></td>
<td>Building construction, including refurbishment</td>
<td>Energy uses from published literature (shown in Chapter 5.4).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(b) Use (Operational)*</td>
<td>Use of electricity and fuels for cooling, lighting and ventilation</td>
<td>DesignBuilder as a simulation software based on the Energy-Plus solving engine. The results were validated by comparing them with published results from the literature (shown in Chapter 6).</td>
<td>DesignBuilder and Excel spreadsheet</td>
<td>Australian national average for commercial building energy consumption</td>
</tr>
<tr>
<td>(C) End of life (Demolition)</td>
<td>Building demolition</td>
<td>Average CO$_2$-e emissions associated with demolition extracted from published literatures (shown in Chapters 5 and 7).</td>
<td>Excel spreadsheet</td>
<td>extracted from published literatures</td>
</tr>
<tr>
<td></td>
<td>Total embodied CO$_2$-e emissions of the building during its life cycle</td>
<td>Phase (a+b+c); (shown in Chapter 7)</td>
<td>Combining the results of a, b and c</td>
<td>---</td>
</tr>
</tbody>
</table>

*This type of highly glazed office building risked overheating during the summer and winter periods. As such, the cooling load is the dominant load across all five climates studied (Robati et al. 2017).
3.8 Uncertainty analysis of Life cycle embodied CO\textsubscript{2}-e emissions uncertainty analysis

As shown in section 2.11, little is known about the uncertainties associated with the embodied CO\textsubscript{2}-e emissions of building materials over the life cycle of buildings. Chapter 5 in this study aims to quantify uncertainties associated with the calculation of life cycle of embodied CO\textsubscript{2}-e emissions buildings (Cradle to Grave). That Chapter assesses the life cycle of CO\textsubscript{2}-e emissions from four different construction forms used (section 3.5) in a typical 15 storey office building in Australia. Monte Carlo techniques were used in the Chapter to quantify the variability associated with environmental impact (CO\textsubscript{2}-e emissions) for each construction material and structural system. Monte Carlo is a statistical method that uses random values from input parameters and presents a distribution for the output parameter as examined by numerous researchers (Bisinella et al. 2016; Bojacá & Schrevens 2010; Ciroth et al. 2004; Fitch & Cooper 2005; Grant et al. 2016). Section 5.4 provides detailed information pertaining to the main methodological stages.

3.9 Analysis of Life cycle cost

Assessing the life cycle costs includes the initial cost, the operating and maintenance costs, and the disposal cost (as shown in Figure 3-7). For the purpose of this study, the initial cost includes the expenses associated with the manufacturing materials and construction of the building. The operating and maintenance costs include the running energy and material replacement costs during the lifetime of the building. The disposal costs include the demolition costs.
The initial costs associated with building materials and construction activities are taken from the Australian construction handbook based on 2016 data (Rawlinsons 2016).

The operating energy cost is estimated based on the annual energy consumption (based on energy simulation results) and estimated future Australian energy prices (Economics 2015; Jacobs 2016) for the cost of energy up to 2040. A future cost analysis is then used to extend the energy costs from 2040 to 2066 (50-year lifetime of the building- base year 2016). The Present Value (PV) of operational costs is estimated based on Equation (3-1) with a 7% discount as a nominal rate per year (Lawania & Biswas 2016).

\[
PV \text{ of operating cost} = \sum_{y=1}^{building \ lifetime=50} \frac{future \ cost}{(1+\text{discounted rate})^{\text{occurring year}}} \quad (3-1)
\]

The PV replacement costs for the building materials are estimated as having a shorter lifetime than the buildings (50 years) (Rauf & Crawford 2012). The replacement cost

---

**Figure 3-7 Life cycle cost of building**

The initial costs associated with building materials and construction activities are taken from the Australian construction handbook based on 2016 data (Rawlinsons 2016). The operating energy cost is estimated based on the annual energy consumption (based on energy simulation results) and estimated future Australian energy prices (Economics 2015; Jacobs 2016) for the cost of energy up to 2040. A future cost analysis is then used to extend the energy costs from 2040 to 2066 (50-year lifetime of the building- base year 2016). The Present Value (PV) of operational costs is estimated based on Equation (3-1) with a 7% discount as a nominal rate per year (Lawania & Biswas 2016).

\[
PV \text{ of operating cost} = \sum_{y=1}^{building \ lifetime=50} \frac{future \ cost}{(1+\text{discounted rate})^{\text{occurring year}}} \quad (3-1)
\]

The PV replacement costs for the building materials are estimated as having a shorter lifetime than the buildings (50 years) (Rauf & Crawford 2012). The replacement cost
is calculated based on the current price of the materials and an escalation (inflation) rate of 3% (RBA 2016). Equation (3-2) is used to represent the present value for maintenance cost (Fuller 2010).

\[
PV \text{ of maintenance cost} = \sum_{y=1}^{50} \frac{\text{current material price} \times (1 + \text{escalation rate})^{\text{occurring year}}}{(1 + \text{discounted rate})^{\text{occurring year}}}
\]  

(3-2)

The costs associated with demolition at the end of life are estimated based on the future cost analysis (shown in Equation 3-3). Future costs are estimated based on the national average cost of demolition per square metre ($112/m^2) for a fifteen storey reinforced concrete frame and slab buildings (Rawlinsons 2016) over a 50 year lifetime of buildings.

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

(3-3)

The expenses associated with refurbishment and development of the external site are not included in this study.

3.10 Environmental impact cost analysis

The CO$_2$-e emissions (in section 3.6) calculated for each stage of the designed buildings (production, construction, use, and end of life) are used to quantify the relative environmental impact of several structural design choices. These structural choices include two flooring systems (Waffle slabs and Flat slabs) with two different types of concrete (Normal weight and Ultra-lightweight concrete). The total embodied CO$_2$-e emissions value of each phase of the building is then converted into costs. The monetary value of CO$_2$-e emissions is based on Adams et al. (2014) method and the Australia Emissions Trading Scheme (Combet 2012) with an inflation rate of 3% per year (RBA 2016). Future CO$_2$-e emissions costs are discounted at a rate of 7% per year.
(Lawania & Biswas 2016). Equation 3-4 is used to determine the present value of CO2-e emissions over the lifetime of the buildings. The base year (2016) is used for all calculations.

\[
PV \text{ of environmental cost} = \sum_{y=1}^{50} \frac{\text{Current CO}_2\text{-e price} \times (1+\text{escalation})^{\text{occuring year} \times \text{disocunted rate}^{\text{occuring year}}}}{(1+\text{discounted rate})^{\text{occuring year}}} \tag{3-4}
\]

Figure 3-8 represents the methodology used for the environmental cost analysis in this study.

**Figure 3-8 Environmental cost estimation method**

The economic value obtained from the life cycle costing assessment and the environmental cost assessment is used to select the most suitable structural design; the resulting cost is useful because it compares total costs across the reference benchmark and the alternative designs. This then enables the comparison data to be described with a single global assessment parameter. A summary of this framework is shown in Figure 3-9 (Tsimplokoukou et al. 2014).
3.11 Summary

This Chapter describes the research methodology in order to include the life cycle carbon emissions and energy consumption in the process of structural design during decision making. This research methodology is used to evaluate the CO₂-e emissions associated with several construction forms and structural concrete. The structural analysis part included in this study also examines the performance-based design of the buildings by considering the limit state method. The last step of this research methodology combines the results obtained from a lifetime CO₂-e emissions study and the structural design and expresses them in terms of their economic value. All the CO₂-e emissions impacts are converted into CO₂-e emissions, which is then multiplied by the Australian National carbon price.

The integrated structural and lifetime CO₂-e emissions costs are presented in terms of monetary units to provide a single global sustainable parameter that could be used to evaluate the alternative structural design of buildings. The results of this framework are used as an evaluation and comparison method across alternative structural design solutions. The following Chapters describe the environmental assessment and energy
performance analysis during operation, as well as the economics of the designed buildings.
Chapter 4 Incorporating an environmental evaluation and the thermal properties of concrete mix designs

Contribution of the candidate to the Published Work

The contribution of the candidate in the published paper was 90%. He co-authored them with his main and co-supervisors. The candidate collected and analysis data and wrote the paper. Other authors reviewed the papers and provided useful feedback for improvement.

Citation: Published

4.1 Introduction

Chapter 3 proposed a methodology to integrate the environmental, structural, and economic aspects of a building structure over its life cycle. The literature review in Chapter 2 highlighted the sustainable structural design strategy defined as a way of selecting structural materials and forms to reduce their impact through lifetime of a project (Pongiglione & Calderini 2016). One of the main challenges in the sustainable design of buildings is to improve their energy efficiency over its lifetime whilst simultaneously reducing the environmental impact of the initial design.

As section 2.9 shows, recent advances in concrete technology result in a lower environmental impact due to the application of supplementary cementitious materials and recycled aggregates; there are also improvements in thermal properties due to the application of admixtures. However, the correlation between the environmental impact (Cradle to Gate) and thermal performance of concrete mix designs has not been researched adequately because the GHG emissions associated with producing the individual components of concrete must be considered with greater refinement. This Chapter correlates the impact of selecting a concrete mix design in terms of CO2-e emissions with the resulting thermal conductivity and density at the design stage of buildings.

4.2 Low carbon concrete material

Concrete is the most widely used construction material in the building industry and as such consumes the second highest amount of natural resources (ISO15673 2005). The main constituents of general purpose concrete are cement, water, and aggregates, and the most carbon intensive components in the manufacture of concrete are cement and
aggregates. A report released by the United States Geological Survey shows that the global production of cement increased by 100 million tonnes in one year to 4.18 billion tonnes in 2014 (Survey 2015). The American Portland Cement Association (PCA) estimates that the consumption of cement will continue to increase into the future (PCA 2015).

Concrete is a popular material because it has excellent mechanical and durable properties, it is also adaptable, relatively fire resistant, and generally available and affordable. Concrete can absorb and retain energy for a long period of time, an action which reduces energy consumption by transferring heat in a natural daily cycle through the structural components (thermal mass) of the building. The mass components reduce the fluctuations in temperature in building spaces which in turn decreases the associated peak heating and cooling loads (Torgal & Jalali 2011).

Through its high thermal mass, a concrete slab will absorb heat during the day and release it back into the room at night. The relatively high specific heat of solid concrete makes it attractive as a passive thermal store, so an appropriately designed concrete mix can offer the benefits of thermal performance by reducing the consumption of heating and cooling energy in buildings (Anderson & Silman 2009; Appleby 2012).

This situation raises the question about how best to design a concrete mix with respect to its strength, thermal properties, environmental impact, and CO₂-e emissions intensity. This Chapter seeks to identify the environmental impact and thermal performance of different concrete mix designs by examining the impact of CO₂-e emissions on the thermal properties of concrete.
4.3 Thermal performance of concrete

Concrete is one of several building materials that possess high thermal properties. In cold seasons, high thermal mass building elements that contain concrete, such as walls and floor slabs, absorb radiant heat from the sun during the day and gradually release it back into the system (space) during the night when the outside temperatures drop (Lemay & Leed 2011). The distinct benefit of high thermal mass is to moderate changes in the peak load of energy requirements due to fluctuations between inside and outside temperatures. High thermal mass causes a time lag between internal and external temperatures (Figure 4-1), but it also stores heat which dampens the fluctuations between peaks; this often improves the thermal comfort and decreases the demand for energy for heating and cooling (Lemay & Leed 2011). Besides its thermal mass, the thermal properties of a concrete mix design such as conductivity, also influence passive heating design strategy. An optimum design of concrete mix could either reduce the escape of passive heating before being absorbed or re-release stored heat before the colder night (DIIS 2013).

Figure 4-1 Damping and lag effect of thermal mass (Lemay & Leed 2011)
The thermal conductivity of concrete mix designs is influenced by the thermal properties of the cement, aggregates, and the existing moisture (ACI122R 2014). The thermal conductivity of concrete depends on the type of aggregates used in the mixture. Some published construction properties databases associate thermal conductivity with the density of concrete, for example ACI122R (2014) and CIBSE (2006); this means that some thermal properties of concrete mixes at the initial stage of the structural design of buildings can be considered. This Chapter quantifies the thermal conductivity of different concrete mix designs.

4.4 Environmental aspects of concrete

The basic constituents of concrete are binder (cementitious materials), coarse and fine aggregates (or inactive mineral filler), and water. The properties and combinations of these materials affects the various admixtures, and how it is handled during construction determines the properties of the in-situ concrete.

A major source of greenhouse emissions during the production of concrete is Portland cement; indeed the cement sector is responsible for producing 2,823 million metric tons (Mt) of embodied CO$_2$-e emissions in 2010 (Kajaste & Hurme 2016); this is almost 9% of global CO$_2$-e emissions from burning fossil fuels in 2010 (Kajaste & Hurme 2016). Traditional methods of responding to this issue are to develop energy efficient cement production plants through improved technology, change the energy sources used and use substitutes for clinker such as fly ash and ground granulated blast furnace slag (Ishak & Hashim 2015; McLellan et al. 2012; Rahman et al. 2015; Worrell 2008).
The concrete industry is addressing some of the worries about environmental issues by supplementing or replacing the use of cement and other components associated with high embodied CO₂-e emissions. Several researchers have studied the possibility of replacing cement in concrete with recycled materials (de Castro & de Brito 2013; Ingrao et al. 2014; Jacoby & Pelisser 2015). The use of alternative cementitious materials remains the main path to reducing embodied CO₂-e emissions in the concrete industry (Mehta 2002). Wimpenny (2009) conducted a study in low CO₂-e emissions alternatives to concrete by exploring the strategies being adopted and developed in 12 countries around the world; his results are classified into the seven groups shown in Table 4-1.

Table 4-1 Embodied CO₂-e emissions for cementitious materials (Wimpenny 2009)

<table>
<thead>
<tr>
<th>Group</th>
<th>Example</th>
<th>Suggested quantities</th>
<th>embodied CO₂-e emissions</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alternative cementitious materials</td>
<td>Fly ash</td>
<td>40%</td>
<td>Medium</td>
<td>(Newlands et al. 2012; Wimpenny 2009)</td>
</tr>
<tr>
<td></td>
<td>Slag</td>
<td>80%</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Silica fume</td>
<td>10%</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Metakaolin</td>
<td>10%</td>
<td>Very high</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Municipal solid waste</td>
<td>-----</td>
<td>Medium</td>
<td></td>
</tr>
<tr>
<td></td>
<td>incinerator ash (MSWIA)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-Portland cement binders</td>
<td>Geopolymer</td>
<td>-----</td>
<td>Low</td>
<td>(McLeod 2005; Taylor &amp; Collins 2006)</td>
</tr>
<tr>
<td></td>
<td>Calcium sulphate based</td>
<td></td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Calcium sulfoaluminate</td>
<td></td>
<td>High</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Magnesite based</td>
<td></td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Low cement concrete</td>
<td>Lean Concrete</td>
<td>-----</td>
<td>Medium</td>
<td>(Wimpenny 2009)</td>
</tr>
<tr>
<td>Ultra-high strength concrete</td>
<td>Fibre reinforced superplasticiser silica fume concrete (FRSSFC)</td>
<td>-----</td>
<td>Medium</td>
<td>(Wimpenney 2009)</td>
</tr>
<tr>
<td>------------------------------</td>
<td>---------------------------------------------------------------</td>
<td>------</td>
<td>--------</td>
<td>------------------</td>
</tr>
<tr>
<td>Changes in Portland cement manufacture</td>
<td>Oxygen enrichment of kiln atmosphere to enhance burning</td>
<td>-----</td>
<td>Medium</td>
<td>(Taylor &amp; Collins 2006)</td>
</tr>
<tr>
<td>Belite cements</td>
<td>-----</td>
<td>Very high</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alinite and Fluoralinite cement</td>
<td>-----</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Portland limestone cement</td>
<td>-----</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alternative binder types</td>
<td>Bituminous based materials (Agent C)</td>
<td>-----</td>
<td>Very low</td>
<td>(Wimpenney 2009)</td>
</tr>
<tr>
<td>Carbon capture</td>
<td>Sequestering carbon from the kiln capturing carbon in the concrete, e.g. Hemp (Lime based binder and hemp)</td>
<td>-----</td>
<td>Very low</td>
<td>(McLeod 2005)</td>
</tr>
</tbody>
</table>

The most commonly used alternative cementitious materials are Ground Granulated Blast Furnace Slag (GGBFS) and coal combustion fly ash. GGBFS is a by-product of iron and steel making and fly ash is a by-product of burning coal, mainly for generating electricity. These cementitious materials are used to replace a portion of the cement in concrete mix designs. The process used to produce fly ash and GGBFS involves less greenhouse gas emissions than ordinary Portland cement (Van den Heede & De Belie 2012).

Fly ash is widely available which, if not used in concrete, is an industrial waste with serious disposal problems. Worldwide, most of the annual production of fly ash is disposed of as waste material in ash dams or in a landfill (Dhir 2006). In Australia, about 20% of fly ash produced in coal-fired power stations is used in construction industry (Wang & Wu 2006). The Australian Standard, AS3582.1, sets specific requirements for fly ash and has classified it into three grades (fine, medium and
coarse)(AS3582.1 2016). If the physical properties of fly ash do not comply with the AS3582.1 Standard requirements it cannot be used as a supplementary material in the cement and concrete industry (Dhir 2006). The proportion of fly ash in blended cement typically changed from 15% to 30% and for some particular applications, it can be increased to 50% and 60% (Malhotra & Mehta 2002; Marsh 2003). The positive contribution of fly ash for reducing concrete embodied CO₂-e emissions can be up to 44% when it substitutes 40% of Portland cement in a typical concrete mix design (ADAA 2012), however, this decrease in the use of coal might also have a negative impact on the supply of fly ash (Gursel et al. 2016).

Other supplementary materials such as GGBFS can also be used to replace Portland cement, in fact, substituting a portion of Portland cement with GGBFS can substantially reduce the negative environmental impact of concrete (Obuzor et al. 2011). Fly ash and GGBFS can be added separately to a concrete mix, however, unlike fly ash, the amount of available GGBFS is limited. The worldwide production of GGBFS is only 25 million tonnes per year (Malhotra 2006). The proportion of GGFS in concrete typically varies from 40% to 60% of the overall amount of blended cement (Virgalitė et al. 1995).

Other supplementary cementitious materials are silica fume, rice husk ash, and recycled ground glass, but their availability is limited, unlike fly ash, so their costs are much higher (Glavind 2012).

Geopolymer concrete is another alternative where an alkali activated aluminosilicate material is used instead of traditional cement binders (Huiskes et al. 2016). Geopolymers generally have a lower embodied CO₂-e emissions than cement but are much more expensive to produce (Berndt et al. 2013).
Meanwhile, there are some barriers to implementing these newer types of materials to achieve lightweight and/or geopolymer concrete such as regulatory, technical, supply chain, and the cost of geopolymer concrete (Cabeza et al. 2013; Duxson & Provis 2008; Van Deventer et al. 2012). Several research programs are currently trying to remove these barriers to allow for a wider application of geopolymer and/or lightweight concrete.

Aggregates affect the physical properties of concrete (grade, moisture absorption, thermal conductivity, etc.), but they can also be reused as raw materials in the concrete at the end of life (Gravitt 2013). The actual choice of aggregates is very much related to the local supply chain because quarries with enough natural aggregates are rapidly being depleted in some regions and countries, which means the tendency to use crushed and manufactured aggregates is increasing (Rao et al. 2007). From an emissions point of view, a distinction must be made between natural and crushed aggregate; natural aggregates such as sand and gravel are the result of weathering and erosion and do not require any processing other than collection and transportation, whereas crushed aggregates such as manufactured sand, are mined from quarries and require mechanical crushing. Flower and Sanjayan (Flower & Sanjayan 2007) showed that granite/hornfels as a crushed aggregate has GHG emissions of 45.9 kg CO$_2$-e/tonne and basalt as natural aggregates has GHG emissions of 35.7 kg CO$_2$-e/tonne (Flower & Sanjayan 2007).

The demand for water for concrete depends on the design of the mixture and the use of plasticising additives. Water in concrete leads to minimal embodied CO$_2$-e emissions, which leaves the cement, the coarse and fine aggregates, and GGBFS and fly ash as having the main environmental impact.
Previous studies into the environmental impact of producing cementitious materials and aggregates has already yielded several estimates of the embodied CO₂-e emissions per tonne of concrete (Flower & Sanjayan 2007; Malhotra 2006; Mehta 2002; O’Brien et al. 2009). The embodied CO₂-e emissions is calculated by multiplying the embodied CO₂-e emissions coefficients from the proposed databases (Alcorn 2003; Crawford 2011; eTool 2014; Hammond et al. 2011) for each grade of concrete by the quantity of concrete. However, individual concrete components have not received enough attention, which means the GHG emissions associated with each individual component of concrete must be properly investigated (Flower & Sanjayan 2007). Furthermore, the relationship between embodied CO₂-e emissions, thermal conductivity, and alternative cementitious materials has not been determined well enough, which is why the primary objective of this Chapter is to identify the relationship between low embodied CO₂-e emissions and low thermal conductivity for a large number of concrete mix designs. This Chapter analyses different concrete mix designs and compares the results while sourcing inputs from a number of available inventory databases.

4.5 Methodology

4.5.1 Materials and mix designs

This Chapter investigates 90 different concrete mix designs where the two primary performance variables are the grade and density. These concrete mix designs have been collected from 8 published journal papers and databases (Berndt 2015; CCAA 2015; Damdelen et al. 2015; Marinkovic et al. 2010; O’Moore & O’Brien 2009; Tošić et al. 2015; Wu et al. 2015; Yun et al. 2013; Zhang & Poon 2015); they represent some
conventional (normal weight) and some advanced methods of concrete admixture (Marinkovic et al. 2010; Wu et al. 2015; Yun et al. 2013; Zhang & Poon 2015) that result in lightweight and ultra-lightweight concrete. Table 4-2 summarises the concrete grades and the 90 mix cases of different batches of concrete that are analysed in this Chapter. Novel forms of concrete admixture (such as Mix 27-41) are included in this Chapter to illustrate their thermal properties and environmental impact because they are not covered in mainstream studies. These concrete grades range from 28 MPa to 87 MPa; their concrete mix designs and ingredients are shown in Appendix A.

**Table 4-2 Summary of concrete batches**

<table>
<thead>
<tr>
<th>Mix No.</th>
<th>Concrete Grade (MPa)</th>
<th>Composition of mix</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mix 1-3</td>
<td>32,40</td>
<td>Portland cement, GGBFS, fly ash natural aggregates, recycled aggregates, manufactured sand, fine natural river sand Water reducing Potable water, Reclaimed water</td>
<td>CCAA (2015)</td>
</tr>
<tr>
<td>Mix 4-9</td>
<td>31.6-42.7</td>
<td>Portland cement, natural aggregates, manufactured sand, Lightweight aggregate*, Furnace bottom ash Water reducing Potable water</td>
<td>Zhang and Poon (2015)</td>
</tr>
<tr>
<td>Mix 27-41</td>
<td>33-69.4</td>
<td>Portland cement, cenosphere, silica fume natural aggregates and manufactured sand Superplasticiser, shrinkage reduction, Viscosity modify agent, Polyethylene fibers, Silane</td>
<td>Potable water</td>
</tr>
<tr>
<td>Mix 42-57</td>
<td>38-55</td>
<td>Portland cement, GGBFS, fly ash, silica fume natural aggregates, recycled aggregates,</td>
<td>------</td>
</tr>
<tr>
<td>Mix 58-69</td>
<td>23-43.9</td>
<td>Portland cement, fly ash natural aggregates, Lightweight aggregate*, Glass bubble</td>
<td>------</td>
</tr>
</tbody>
</table>
This Chapter considers each individual component of concrete in order to estimate the equivalent greenhouse gas emissions and thermal conductivity of a particular design mix. The embodied CO$_2$-e emissions for a variety of concrete mix designs is quantified by collecting the relative embodied CO$_2$-e emissions coefficients for each individual component of concrete from existing studies (ADAA 2016; Flower & Sanjayan 2007; McRobert 2010; Rouwette 2012).

The estimated emissions coefficient for each material is then multiplied by the respective quantity of material, and then the resulting embodied CO$_2$-e emissions is summed up for each mix design. This comparison includes the results obtained from this Chapter that were compared to six publicly available Australian and England embodied CO$_2$-e emissions data inventories, namely; Crawford (Crawford 2011), Alcorn (Alcorn 2003), eTool (eTool 2014) and BPIC (an average industrial practice database) (BPIC 2014) and AusLCI (AusLCI 2016), ICE (Hammond et al. 2011) from England. Since the study by Crawford covers embodied energy rather than embodied CO$_2$-e emissions, a conservative coefficient of 10% (based on the ratio used in eTool database) is used to convert data into embodied CO$_2$-e emissions (kg CO$_2$-e emissions). A linear interpolation is used in the Crawford databases to estimate the coefficient of embodied CO$_2$-e emissions for every grade of concrete proposed in the

<table>
<thead>
<tr>
<th>Mix</th>
<th>50-75</th>
<th>Portland cement,</th>
<th>Natural aggregates</th>
<th>-----</th>
<th>Potable water</th>
<th>Marinkovic et al. (2010)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mix</td>
<td>76-79</td>
<td>Portland cement,</td>
<td>Natural aggregates, recycled aggregates,</td>
<td>-----</td>
<td>Potable water</td>
<td>Tošić et al. (2015)</td>
</tr>
<tr>
<td>Mix</td>
<td>80-90</td>
<td>Portland cement,</td>
<td>Natural aggregates</td>
<td>-----</td>
<td>Potable water</td>
<td>O’Moore and O’Brien (2009)</td>
</tr>
</tbody>
</table>

*Lightweight aggregate consists of manufactured aggregate (shale, slate and clay) and Glass bubble. 

130
concrete mix data of this Chapter. With the ICE database, a linear interpolation is used to estimate the embodied CO$_2$-e emissions coefficient when different percentages of cement are replaced with slag and/or fly ash. Calculating the thermal conductivity of each design mix is done by following the ACI122R (2014) guidelines which propose that the thermal conductivity of a concrete mixture is based on the individual material properties of which the mixture consists (aggregate), and the oven dry density of the mixture (kg/m$^3$).

4.5.2 *Embodied carbon dioxide equivalent emissions*

The emissions factors for binders, aggregates, and admixtures are from Flower and Sanjayan (2007) and are based on the Australian greenhouse office factors and method workbook (AGO 2004). The emissions factor for recycled aggregates comes from the ARRB Group report (McRobert 2010). The embodied emissions associated with manufactured aggregates are considered to be the same as natural aggregates with regards to the upstream stage of the production process in Australia (Chandra & Berntsson 2003). The emissions associated with potable water and captured water are based on the results of Rouwette (2012). The boundary of the system for calculating the total embodied CO$_2$-e emissions is depicted in Figure 4-2. This Chapter considers the embodied CO$_2$-e emissions associated with concrete and concrete materials from cradle to gate; this means it includes all the steps from extraction of raw materials, transport to the concrete plant, mixing, and the production of concrete by considering the relevant consumed energy (Diesel fuel, LPG fuel and electricity). The process of transportation and the placement of concrete is excluded from this Chapter. Table 4-3
summarises the final embodied CO\textsubscript{2}-e emissions coefficients that are related to individual concrete components based on Australian data.

Figure 4-2 Concrete embodied CO\textsubscript{2}-e emissions system diagram

Table 4-3 Final embodied CO\textsubscript{2}-e emissions coefficients

<table>
<thead>
<tr>
<th>Activity</th>
<th>Material</th>
<th>Emissions coefficient</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Binder</strong></td>
<td>Type of Portland cement</td>
<td>0.820</td>
<td>(ADAA 2016; Flower &amp; Sanjayan 2007)</td>
</tr>
<tr>
<td></td>
<td>Ground Slag ; Ground Granulated blast furnace</td>
<td>0.143</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fly ash or pulverized fuel ash</td>
<td>0.027</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Furnace bottom ash</td>
<td>0.027</td>
<td></td>
</tr>
<tr>
<td></td>
<td>cenosphere</td>
<td>0.027</td>
<td></td>
</tr>
<tr>
<td><strong>Aggregates</strong></td>
<td>Natural aggregates</td>
<td>0.0459</td>
<td>(Flower &amp; Sanjayan 2007; McRobert 2010)</td>
</tr>
<tr>
<td></td>
<td>Recycled aggregates</td>
<td>0.004</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Manufactured Sand</td>
<td>0.0139</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fine natural river sand</td>
<td>0.0139</td>
<td></td>
</tr>
<tr>
<td><strong>Admixture</strong></td>
<td>Water reducing admixture</td>
<td>2.2 \times 10^{-6}</td>
<td>(Flower &amp; Sanjayan 2007)</td>
</tr>
<tr>
<td></td>
<td>Superplasticiser</td>
<td>5.2 \times 10^{-6}</td>
<td>(Flower &amp; Sanjayan 2007)</td>
</tr>
<tr>
<td><strong>Water</strong></td>
<td>Potable water</td>
<td>7 \times 10^{-4}</td>
<td>(Rouwette 2012)</td>
</tr>
<tr>
<td></td>
<td>Captured/ Reclaimed water</td>
<td>7 \times 10^{-5}</td>
<td></td>
</tr>
</tbody>
</table>
4.6 Results and discussion

4.6.1 Embodied emissions

The resulting cradle to gate life cycle embodied CO$_2$-e emissions for the 90 concrete mixtures are shown in Figure 3. The quantities of embodied CO$_2$-e emissions relate to 1 m$^3$ of concrete, and as the results in Figure 4-3 show, the amount of embodied CO$_2$-e emissions is influenced by variations in the concrete mixture.

**Figure 4-3 Embodied CO$_2$-e emissions for different grades of Concrete**

Figure 4 shows the variation of embodied CO$_2$-e emissions per m$^3$ of concrete for the 32-35 MPa and 38-42 MPa groups of concrete. This data is categorised into common standardised grades of 32 and 40 MPa due to variability in the expected concrete strength (Neville 2012), and because these two categories are popular in the structural design of buildings. The results of graphically depicted embodied CO$_2$-e emissions show the variations and the different mix designs for the two selected groups. The statistical distribution of data shows interquartile ranges between 72.9 and 103.1 Kg CO$_2$-e /m$^3$ for group 32-35MPa and 38-42 MPa respectively (Figure 4-4).
Concrete with a grade of 32-35MPa has an embodied CO₂-e emissions range from 187.2 to 417.5 kg CO₂-e/m³ by a central tendency of 277 kg CO₂-e/m³. The results shown in Figure 4-5 indicate that a mix number 13 and mix number 32 achieved the lowest and highest embodied CO₂-e emissions respectively, compared to the other mixes. For mix design number 13, 65% of the binder is blast furnace slag and 35% is general Portland cement. The mix with the lowest emissions (mix design number 32) has 58% general Portland cement, 37% cenosphere, and 5% silica fume.

For group 38-42 MPa, the embodied CO₂-e emissions was calculated to vary from 211 to 509 kg CO₂-e/m³ by a median value of 311 kg CO₂-e/m³ as shown in Figure 4-6. Mix number 22 and 36 produced the lowest and highest amount of embodied CO₂-e emissions per m³ of concrete, respectively. The mix 22 binder contains 35% Portland cement and 65% blast furnace slag. Mix 36 consists of 55% Portland cement, 40% cenosphere, and 5% of silica fumes.
Various methods have been proposed to reduce the embodied CO\textsubscript{2}-e emissions of Portland cement (Berndt et al. 2013; Damtoft et al. 2008; Gartner 2004; Worrell 2008). For instance, producing cement can be more efficient by reducing the proportion of clinker and replacing it with ground granulated blast furnace slag (GGBFS). Moreover, supplementary cementitious and pozzolanic materials such as GGBFS, fly ash, silica fumes, rice husk ash, and metakaolin have been considered as a replacement for Portland cement (Berndt et al. 2013; Srinivasreddy et al. 2013; Whiting et al. 2012).

This Chapter quantifies the effect of replacing portions of Portland cement with fly ash and GGBFS. The results show that concrete mixes with fly ash have 8% to 30% less embodied CO\textsubscript{2}-e emissions compared to a mix with 100% Portland cement (mix 80-85), and GGBFS can reduce embodied CO\textsubscript{2}-e emissions by 15.5% in a concrete
mixture (mix 86-90). Moreover, the emissions associated with producing concrete are related to parameters such as the availability of raw materials in the region and the amount of emissions produced during transportation. This Chapter considered the embodied CO\textsubscript{2}-e emissions associated with concrete and concrete materials from cradle to gate, so parameters such as transportation, region, etc., are not taken into account.

4.6.2 Variations in embodied CO\textsubscript{2}-e emissions coefficient

The estimated embodied CO\textsubscript{2}-e emissions for the two selected grade groups of concrete are compared between the Crawford, ICE, Alcorn, eTool, BPIC and AusLCI inventory embodied CO\textsubscript{2}-e emissions databases. Figure 4-7 and Figure 4-8 illustrate the embodied CO\textsubscript{2}-e emissions across mixture designs for 32-35 MPa and 38-42 MPa grades.

![Figure 4-7 Embodied CO\textsubscript{2}-e emissions across inventory databases for 32 MPa concrete](image)

* Include Silica fume.
Figure 4-8 Embodied CO₂-e emissions across inventory databases for 40 MPa concrete

This comparison shows that the amount of embodied CO₂-e emissions for grade 32 MPa can vary from 62.8 to 495.9 kg CO₂-e /m³ of concrete depending on the type of mix design and inventory database. Similarly, a much different embodied CO₂-e emissions for grade 40MPa concrete came from (from 70.3 to 616.3 kg CO₂-e /m³ of concrete) across the different mix designs and databases. The resulting embodied CO₂-e emissions based on Crawford, eTool and BPIC databases have treated concrete as one specific product and have proposed an individual coefficient for each grade of concrete regardless of the mix of ingredients. The minor changes (less than 4%) in each database, including BPIC, eTool, and Crawford are due to changes in the density of concrete mix designs and the embodied CO₂-e emissions coefficients that are a function of concrete density. Alternatively, the comparison of concrete mixes from the ICE database and this Chapter (using the coefficients of Table 4-3) show that mix designs 13 for 32 MPa concrete and 22 for 40 MPa concrete have the lowest embodied CO₂-e emissions due to replacing 65% of cement with blast furnace slag. As expected,
the maximum embodied CO$_2$-e emissions was recorded for mix 32 and mix 36 for groups 32 and 40 MPa, respectively because no supplementary cementitious materials are used (i.e. 100% Portland cement was used).

The data in Figures 4-7 and 4-8 show that the results based on AusLCI and Alcorn analysis differ by less than 4%, while both databases can show variations between the mix designs. Like the results of this Chapter, the highest embodied energy are for mix designs 36 and 32 for a grade of 32 and 40 MPa, respectively. The lowest embodied emissions are archived through mix designs 13 and 22.

The current databases cannot address the effect of silica fume and cenosphere very well because alternative cementitious materials are used in concrete mix designs 32, 36, and 49 (as shown in Figure 4-7 and Figure 4-8). However, it is reasonable to assume there is no environmental impact associated with silica fumes because they are a by-product of the production of metallurgical grade silicon (Crossin 2012). Furthermore, since the embodied CO$_2$-e emissions associated with the cenosphere is similar to the CO$_2$-e emissions of fly ash, it was assumed to be the same as fly ash in the paper because both materials are by-products from the production of power within coal fired power stations (ADAA 2016).

The embodied CO$_2$-e emissions from using different inventory databases are summarised in Figures 4-9 and 4-10. The embodied CO$_2$-e emissions values across the Alcorn, Crawford, and eTool databases vary from 255 to 540 kg CO$_2$-e /m$^3$ for group 32-35 MPa and from 290 to 590 kg CO$_2$-e /m$^3$ for group 38-42 MPa. The differences could be due to variations in the method used to analyse each database, to different system boundaries, and to sources of data and the quality of input in calculating the upstream process (Dixit et al. 2010).

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The embodied CO2-e emissions factor from ICE database varies for each different mix design, other than mix designs 32, 36, 39, which include silica fume and cenosphere because this database considers different proportions of cement and cementitious material such a slag and fly ash in the concrete. In terms of the maximum proportion of slag in mix designs 13 and 25, the ICE embodied CO2-e emissions coefficients are 62.8 and 70.3 kg CO2-e /m³, but for specific mix designs, the ICE results match closely with those from Crawford (mix 1, 3, 68, 79) and Alcorn (mix 43, 47,61). For mix designs 6 and 9, the ICE results are the same as the results from BPIC.

A comparative analysis between AusLCI, Alcorn, and the current study reveals many variations of embodied CO2-e emissions in concrete mix designs. The average differences are 16 % and 7% for grade 32 and 40 MPa; these differences are due to variations in the embodied CO2-e emissions coefficients for general purpose cement, GGBFS, fly ash, and natural and manufactured aggregates. For instance, AusLCI proposes a factor of 0.994 (tonne CO2-e emissions) for producing an average of 1 tonne of GP cement in Australia, which is 18% higher than the coefficients proposed in Crossin (Crossin 2012) and Flower (Flower & Sanjayan 2007) studies (used in this Chapter). Similarly, AusLCI proposes a higher emissions factor for manufacturing GGBFS and recycled aggregates and lower embodied CO2-e emissions for producing fly ash than this Chapter (based on (Flower & Sanjayan 2007)). The embodied CO2-e emissions associated with the production of natural aggregates is not reported directly in AusLCI, whereas ARRB gives a value of 3.97 kg CO2-e emissions per tonne of materials (McRobert 2010). Moreover, Alcorn’s database does not properly address the embodied CO2-e emissions associated with alternative cementitious materials such as fly ash and GGBFS.
In summary, these variations in the embodied CO$_2$-e emissions of different concrete mix designs could affect the overall life cycle assessment of a building and building materials because the results indicate that one product might be attributed with a lower embodied CO$_2$-e emissions than another product in one database while the same product in another database could be attributed with the same or higher emissions. For example, the results based on AusLCI, Alcorn, ICE and those produced from the additional cases in our study show that mix designs 13, 18, 22, and 26 have the lowest amount of embodied CO$_2$-e emissions in the 90 mix designs because they replaced 65\% of the cement binder with GGBFS. However, the eTool, BPIC, and Crawford databases do not show these differences of embodied CO$_2$-e emissions across the different concrete mixes. Furthermore, variations associated with production,
manufacturing techniques, the type of fuel used, and the source of raw materials and transportation distance across different geographic locations must be considered because they can be quite significant between areas within the same country (Crawford 2011; Crawford 2008). These differences between the databases point to a need for transparency with regard to their ability to analyse individual concrete components. Meanwhile, a summary of the results (Figures 4-9 and 4-10) quantifies the variations which could lead to better comparisons for research that uses these databases.

4.6.3 Thermal conductivity of concrete mix design

A comparative assessment was used to estimate the thermal conductivity of all 90 mixes from ACI122R (ACI122R 2014), while experimental data for mixes 27 to 57 are reported in the relevant published articles (Damdelen et al. 2015; Wu et al. 2015) obtained. The proposed ACI values are from Table 3.a of ACI122R-2014 and are based on practical thermal conductivity design values for normal weight (2240 to 2400 kg/m³), light weight, and ultra-lightweight concrete (less than 1840 kg/m³). Figure 4-11 shows the theoretical and experimental thermal conductivity for all 90 concrete mix designs. This Chapter uses the data from the ACI122R method to ensure consistent comparisons across all mix designs where, as expected, the thermal conductivity is influenced by variations in the concrete mixtures.
This Chapter shows that the type of cement and aggregate affected the density and thermal conductivity, while replacing normal aggregate with lightweight aggregate reduces the density and thermal conductivity of concrete. The data indicates that using lightweight aggregate instead of natural coarse aggregate changes the density of concrete from 2320 to 1727 kg/m$^3$. Moreover, the thermal conductivity of concrete also decreased when lightweight aggregates are introduced into the mix designs. For example, the results of mix 4 and mix 9 indicate that as the proportion of aggregates in these mix designs decreased, the thermal conductivity decreased from 1.96 to 1.16 (W/mK).

Figure 4-12 shows the variation in thermal conductivity per m$^3$ of concrete across mix design groups 32-35 MPa and 38-42 MPa. These variations are the result of changes in the proportion of normal and lightweight aggregates in the concrete mixture. For example, mix designs 32 and 36 have the lowest thermal conductivity and a lower density than all other mix designs in groups 32-35 MPa and 38-42 MPa, respectively.
Figure 4-12 Variations in thermal conductivity between concrete mix designs

A brief review of previously published values shows that the estimated thermal conductivity for grade 32-35 MPa and 38-42 MPa concrete mixes could vary from 3.1 W/(m.K) to 0.36 W/(m.K). For a grade of 32-35 MPa, the lowest and highest thermal conductivity occurs in mix designs 32 and 82, and for 38-42 MPa, the lowest thermal conductivity (0.31 W/(m.K)) occurs in mix design 36.

A comparison of all the embodied CO₂-e emissions obtained from Table 4-3 and the thermal conductivity of mix designs show different correlations between two variables. Figure 4-13 shows the changes of embodied CO₂-e emissions against the thermal conductivity of concrete mix designs; they are also shown in Appendix A.

Figure 4-13 Embodied CO₂-e emissions versus thermal conductivity across all the concrete mix designs
For mix designs 27-41, the results show a positive gradient between changes of thermal conductivity and embodied CO\textsubscript{2}-e emissions; this means the amount of embodied CO\textsubscript{2}-e emissions increases as the thermal conductivity of concrete increases. Note that the rate of changes of embodied CO\textsubscript{2}-e emissions and thermal conductivity for mixes 27-41 are much higher than the other mixes; this is due to the high proportion of Portland cement and low-density aggregates in mixes 27-41. However, the results from several other mix designs show a great deal of scatter in thermal conductivity without changing the embodied CO\textsubscript{2}-e emissions values, and vice versa; this is seen in mix designs 4 to 9, where the changes in thermal conductivities range up to 41% with only a 17% change in embodied CO\textsubscript{2}-e emissions.

Figure 4-14 Embodied CO\textsubscript{2}-e emissions against the thermal conductivity for Grade 32-35 MPa and 38-42 MPa

Figure 4-14 is a comparison between the thermal conductivity and embodied CO\textsubscript{2}-e emissions of the 32-35MPa and 38-42MPa groups of concrete. Note that mixes 27-41 have the lowest thermal conductivity and the highest embodied CO\textsubscript{2}-e emissions, whereas mix designs 10-26 have the lowest amount of embodied CO\textsubscript{2}-e emissions and the highest thermal conductivity in both groups. In group 38-42 MPa, the thermal
conductivities associated with mix design 10-26 do not vary much whereas the embodied CO2-e emissions can range from approximately 200 to 400 kg CO2-e /m³. As discussed previously, the variations shown in Figures 4-11 to 4-14 are associated with changes in the quantity and type of aggregate, and the binder materials in the concrete mix designs. Moreover, a lower thermal conductivity suppresses the energy charging /discharging rates (Fan & Khodadadi 2011), which may have a positive potential effect on the overall energy performance of buildings compared to traditional concrete. Concrete with a low thermal conductivity results has a higher thermal resistance than conventional concrete, which can slow down the heat gain and energy losses for periods of time (Kim, HK et al. 2012; Zhou et al. 2012). However, the optimal range for thermal conductivity of a concrete mix must be able to reduce or escape from passive heating before being absorbed or re-released as a stored heat before the colder night (DIIS 2013). It is therefore essential to consider the environmental impact of concrete mix designs in a more holistic way during the structural design of buildings, and also include the estimated impact on energy performance during the operational phase and end of life (life cycle) of a building. Future research will quantify the potential effect of conventional and novel concrete materials on the thermal performance of buildings.

4.7 Conclusion

A great deal of effort is being put into compiling reliable methodologies for quantifying the environmental impact of concrete production. Some of the embodied emissions databases (eTool, Crawford, BPIC) currently available propose using an individual embodied CO2-e emissions coefficient for each grade of concrete without
considering variations across different mix designs. The findings from this Chapter are consistent with the common literature and confirm that significant reductions in embodied CO₂-e emissions can be achieved by using supplementary cementitious materials such as fly ash, and GGBFS. However, depending on the percentage of cement replaced, fly ash can typically help to reduce the embodied CO₂-e emissions of concrete by 10 to 15% compared to Portland cement. Moreover, GGBFS can also reduce embodied CO₂-e emissions by 15.5% compared to common Portland cement.

The analyses of embodied CO₂-e emissions has shown variations across the different inventory databases which are due to different methods of analysis, the sources of data, and the quality of input data (related to upstream process) in the calculations. This highlights the need for transparency within existing and future databases and imposes a need to extend their capability to model concrete mix designs based on individual components.

When using the ICE database, the results for embodied CO₂-e emissions were sensitive to the concrete mix design because the embodied CO₂-e emissions coefficients in ICE varied according to the different percentages of cement, fly ash, and GGBFS. Indeed the analysis showed that the embodied CO₂-e emissions of a mix design decreased by increasing the proportion of fly ash and GGBFS in the concrete binder. The ICE database was limited in that it could not account for the effects of silica fume and cenosphere in concrete admixture mixes, even though they can be accounted for by including the cenosphere as additional fly ash and considering silica fume as a zero contribution.

The inventory databases from Crawford and eTool use the same embodied CO₂-e emissions coefficients for each grade of concrete without accounting for the effects of
each different concrete component. The calculated of embodied CO₂-e emissions from the BPIC database used average industry values, which resulted in lower embodied CO₂-e emissions than those calculated by the Crawford and eTool databases. However, the analysis based on AusLCI, Alcorn’s analysis, and embodied CO₂-e emissions coefficients (Table 4-3) that were compiled for this study considered the detailed effects of materials in the concrete mix design; it revealed many variations of embodied CO₂-e emissions in the concrete mix designs. However, there are some discrepancies between the results of this study results and the AusLCI analysis due to differences in the embodied CO₂-e emissions factor for Portland cement, fly ash, GGBFS, and the types of aggregates (recycled, natural and manufactured).

This Chapter also showed that the thermal conductivity of concrete is strongly related to the properties of the concrete mixes and the proportions of its constituents. In general, the thermal conductivity of a design mix increases with increasing density and replacing normal aggregates with lightweight aggregates reduces the thermal conductivity of concrete. These lower density concrete mixes with a low thermal conductivity could be beneficial in terms of energy saving during the operational phase of buildings, but lower density concrete mix designs could have higher embodied CO₂-e emissions. Hence, it is crucial to understand and consider the thermal and environmental impacts associated with concrete mix designs in an integrated way and at the design stage of building.

The results of this Chapter can be used to consider reducing the environmental impact and improving the thermal conductivity of concrete while maintaining the desired strength during the early stages of building projects.
The uncertainty associated with calculating the life cycle environmental impact of a builing is addressed in the following Chapter (Chapter 5). Chapter 6 considers the potential impact of concrete mix designs on thermal mass and hence on the energy performance of a building over its operating phase.
Chapter 5

A method of uncertainty analysis for embodied CO$_2$-e emissions impact of building materials in Australia

Contribution of the candidate to the Published Work

The contribution of the candidate in the published paper was 90%. He co-authored them with his main and co-supervisors. The candidate analysed and designed a case study building, analysis uncertainties associated with CO$_2$-e emissions and wrote the paper. Other authors reviewed the papers and provided useful feedback for improvement.

Citation: Published

5.1 Introduction

Chapter 4 presents the environmental impact analysis associated with different structural materials (different concrete mix designs); it revealed that the potential environmental impacts associated with the selection of structural systems and materials can be quantified by using different inventory databases and online tools. The results in Chapter 4 identify some inconsistencies in the calculation of embodied CO₂-e emissions associated with concrete mix designs. This inconsistency between the tools when estimating the environmental impact can lead to large differences in the results of CO₂-e emissions and thus the overall sustainability of buildings. The GHG emissions associated with each individual component of concrete and its production needs greater refinement. This Chapter quantifies the uncertainties associated with calculating the embodied CO₂-e emissions in buildings. To achieve this end, the study assessed the impact of different structural materials and construction forms used in a typical 15-storey office building in Australia, as proposed by the National Standards Development Organisation (NS11401.1 2014). This approach uses to quantify the uncertainties associated with calculating CO₂-e emissions.

5.2 The need for an embodied CO₂-e emissions analysis in construction

The construction industry is a major consumer of renewable and non-renewable natural resources. The construction of new buildings has substantial environmental costs; it is estimated that worldwide, the construction industry consumes 40% of total primary energy, 40% of natural materials, 15% of the world’s freshwater resources, and generates 25% of all wastes and 40–50% of greenhouse gas emissions (GHG) (Ding 2014; Mokhlesian & Holmén 2012; Ramesh et al. 2010).
The use of low CO\textsubscript{2}-e emissions building materials to minimise the industry’s environmental impact has received increasing research and development attention. A holistic approach to the selection of low CO\textsubscript{2}-e emissions building materials should consider the entire material life cycle, including building performance and embodied energy (Berge 2009; Franzoni 2011). The material life cycle includes the extraction of raw materials, manufacturing processes, transportation to the construction site, construction processes, the operational phase, and the end of life recycling and potential for reuse (Ding 2014).

As buildings become more energy efficient, the operational phase of a life cycle assessment will make an increasingly smaller contribution to the total environmental impact, on the other hand material selection will become relatively more important (Thormark 2006). However, selecting low CO\textsubscript{2}-e emissions building materials is a challenging task (Saghafi & Teshnizi 2011), because it requires an analysis of building materials embodying CO\textsubscript{2}-e emissions impact at all stages of the life cycle, as well as an environmental performance of the material as part of operational buildings. This is an ongoing area of research due to a large number of variables and the uncertainty involved in the assessment process.

As shown in section 2.11, there are a number of researchers attempting to quantify the uncertainties associated with the whole life energy performance of buildings (Crawford 2011; Dixit et al. 2010), but there is still a significant gap in current research related to the uncertainty with the embodied energy of materials in the processing, manufacturing, and construction of buildings, relative to operational impacts and uncertainty.
Low CO$_2$-e emissions building design has become the mainstream of research and development in order to minimise the industry’s environmental impact. Previous researchers have highlighted the key points of the sustainable selection of building materials and systems by considering the performance specifications and lowest GHG over the life cycle perspective of buildings at an early stage of design (Berge 2009; Franzoni 2011). The building life cycle embraces the extraction of raw materials, manufacturing process, transportation to the construction site, construction process, operational phase, and the end of life recycling and reuse (Ding 2014).

5.3 Environmental life cycle analysis

An Environmental Life Cycle Analysis (LCA) is a method for identifying and evaluating the environmental aspects of a product through all its activities during its life (ISO14040 2006); this method assesses the materials used and energy released by the system into the environment. Applying a life cycle assessment to the building sector is a particularly complex LCA problem (Ortiz et al. 2009; Taborianski & Prado 2004) due in part to the complexity, size, and intensive use of natural resources in all stages of building (Sharma et al. 2011). The following factors introduce further complexity to LCA in this sector:

- Buildings have a particularly long lifetime, often more than half a century, so it is difficult to predict the whole of lifetime effects of the project from cradle-to-grave (Cabeza et al. 2014);
- The majority of environmental impacts associated with buildings traditionally occurs during the operational phase, and these impacts can be reduced by good design and material selection (Kibert 2012);
During the lifetime of a project, the building may undergo many changes in terms of form and function, changes which can be as significant as the original construction (Stephan & Crawford 2014). Future changes can potentially be considered at an early stage of design to minimise the environmental effects of changes (Crawford 2011);

There are many stakeholders and shareholders involved in the building industry.

British Standard BS EN15978: *Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method* proposes a number of methods for assessing the environmental performance of buildings. The standard proposed calculation method involves four stages in a life cycle assessment of buildings, these include: the product stage (raw materials, transport and manufacture); the construction process (transport, construction and insulation process); the use stage (use, maintenance, repair, replacement and refurbishment), and the end of life (deconstruction, demolition, transport, waste processing and disposal) (EN15978 2011). This system boundary includes the extraction of raw materials, production processes, transportation, and use and disposal.

A number of studies have found that the use stage (operational energy) accounts for 80% to 85% of a building’s life cycle energy consumption (Richman et al. 2009; Sharma et al. 2011). The energy inputs for the production of building products, the extraction and processing of raw materials, and manufacturing and transportation to construction sites are responsible for the remaining 15% to 20% of whole life cycle energy usage of a building (Asdrubali et al. 2013). The contribution made by
construction work, transportation, and final demolition and disposal at the end of life is deemed as almost negligible, at level of approximately 1% (Ruuska & Häkkinen 2015; Sartori & Hestnes 2007).

To understand the role that building materials have on an energy efficient design, the operational and embodied energy implications of building design options must be investigated. Since the operational energy offers most opportunities for energy efficiency, the majority of previous research has focused on reducing it rather than considering all the stages of a building’s life cycle.

Several literature reviews have also highlighted the significance of building materials and embodied energy in a lifetime energy analysis of buildings (Asdrubali et al. 2013; Asif et al. 2007; Dixit et al. 2010; Esin 2007; Kellenberger & Althaus 2009; Rincón et al. 2013; Vieira & Horvath 2008; Wu et al. 2005). The authors found that an appropriate choice of construction and building materials can reduce the embodied energy and embodied CO2-e emissions by 17 % and 30 %, respectively, over the lifetime of buildings (González & García Navarro 2006; Thormark 2006). Asif et al. (2007) studied the life cycle embodied energy and air emissions associated with five commonly used materials (glass, aluminium, wood, ceramic tiles, and concrete) in a Scottish residential house. Concrete was responsible for 60% of the total embodied energy in those buildings. Similarly, Ximenes and Grant (2013) used the life cycle assessment method to determine the GHG associated with several building materials in Australia and found that structural elements consisting of concrete and bricks are responsible for up to 31% and 17% of the total greenhouse impact, respectively. The use of timber in the sub-floor resulted in between 31% and 56% reductions in embodied GHG emissions. Aye et al. (2012) undertook LCA on three forms of
building construction common in Australian and showed that steel structured buildings reduce the consumption of material by almost 78% by mass compared to a concrete structure. However, the steel structure resulted in a 50% increase in embodied energy compared to the concrete structure. They concluded that an efficient use of materials could result in energy savings of up to 81% of embodied energy, and materials (51% by mass).

A number of previous studies identified the variation and inconsistency in the measurements of embodied energy (Buchanan & Honey 1994; Crawford 2013; Dixit et al. 2010; Huang et al. 2010; Langston & Langston 2008). Dixit et al. (2010) found these sources of uncertainty to be: variations in the method of analysis used in each assessment; different system boundaries; and the quality of data sources and input in the calculation of upstream processes. Accordingly, it is important to use methods to quantify the uncertainties associated with the life cycle analysis of buildings and construction materials. This Chapter therefore aims to quantify the uncertainty associated with the embodied CO2-e emissions of a case study building (stages A, B4 and C1-C2 as shown in section 2.8). The analysis of these uncertainties may reveal which inputs are responsible for variations in the embodied CO2-e emissions of buildings, and whether the uncertainties are significant when considering the whole of life environmental impact of buildings.

Following this introduction, the methodology section describes the tools used to analyse the uncertainty associated with the embodied CO2-e emissions of an office building in Australia. A detailed description in section 5.4 illustrates the embodied CO2-e emissions intensity for different building materials and products, followed by a
discussion of the key role of four important materials selected in the overall embodied CO\textsubscript{2}-e emissions of a building.

5.4 Methodology

This Chapter uses a probabilistic based method as the variability of dependent parameters (output variables) as determined by the uncertainty of the independent parameters (input variables). The following paragraphs summarise the workflow and methodology used to quantify the uncertainty associated with a lifetime environmental assessment of the structural design of a building.

This Chapter assesses the uncertainty associated with the embodied CO\textsubscript{2}-e emissions of a typical 15 storey reinforced concrete office building in Australia (NS11401.1 2014). Four commonly used structural floor systems were compared in terms of their embodied CO\textsubscript{2}-e emissions. The four structural frames are a Flat slab, Flat plate, Post-tensioned slab, and Waffle slab that were designed to meet two main AS3600 (AS3600 2009) considerations: strength and serviceability. The boundary for the CO\textsubscript{2}-e emissions environmental assessment of these four structural systems includes the embodied CO\textsubscript{2}-e emissions associated with construction materials from production, construction, and at end life activities (as shown in Figure 5-1).
The sensitivity analysis can be grouped into screening, local, and global methods (Heiselberg et al. 2009); where screening methods are used to evaluate a large number of design parameters; local methods are based on an OAT approach (One parameter At a Time) which is useful for evaluating the relative importance of various design elements, and global sensitivity analysis is where all the parameters are varied at the same time the effect of range and probability density function is considered (Heiselberg et al. 2009; Silva & Ghisi 2014). This Chapter uses global sensitivity and uncertainty analysis via Microsoft Excel function. Based on the literature reviewed, the mean and standard deviation are determined to generate subjective probability distributions for each individual building materials. The cumulative probability distributions as a result of Monte Carlo analysis reveals the variance associated with the embodied CO₂-e emissions of the materials used in the designed buildings.

Figure 5-1 Boundary study of Chapter 5
This Chapter has five stages (as shown in Figure 5-2).

1- List the input parameters and define their probable density functions;

2- Select the probability density function of the input parameters: the relative embodied CO\(_2\)-e emissions, lifetime and the transport distance were extracted from published literature;

3- Perform a random sampling via Microsoft Excel normal distribution function: the input parameters (embodied CO\(_2\)-e emissions, lifetime and transport distance) associated with each building material (Table 5-1) were randomly generated 1000 times to achieve more accurate results (Inyim et al. 2016).

4- Perform an uncertainty analysis: for each 1000 sample data, equation 5-1 was used to generate the probability distribution of all the input parameters. The total result presents the global uncertainty analysis associated with each of the four structural systems.

5- Perform a sensitivity analysis to quantify the magnitude of the change in the estimated embodied CO\(_2\)-e emissions of the building materials. In the last step, the variability of each construction material was quantified and compared against the total embodied CO\(_2\)-e emissions of the building. This stage quantified the relative importance of each building material by considering their relative impact at each individual iteration over the total iterations (1000). The results of this stage provide the magnitude variations of building materials and their impacts on determining CO\(_2\)-e emissions of the building.
Figure 5-2 summarises the workflow and methodology used to quantify the uncertainty associated with a lifetime embodied CO$_2$-e emissions assessment of the benchmark building.
Figure 5.2: the workflow and methodology used in this Chapter
The total embodied CO₂-e emissions is calculated by adding the magnitude of each parameter through the use of Equation (5-1). Equation (5-1) represents lifetime (Cradle to Grave) CO₂-e emissions associated with selection of the building materials and construction systems (Farrance & Frenkel 2014).

\[
T_{CO_2-e} = \sum_{i=1}^{16} \left( \frac{L_T}{L_i} \times ((Q_i \times I_i) + (\frac{Q_i}{C_T} \times I_t \times D_i)) \right) 
\]

(5-1)

Condition: \( \frac{L_T}{L_i} \geq 1 \)

- \( T_{CO_2-e} \) is the total embodied CO₂-e emissions associated with the building materials (Kg CO₂-e emissions); \( L_T \) represents the total lifetime of the building, assumed to be 50 years (AS3600 2009);
- \( L_i \) characterise lifetime associated to the \( i^{th} \) building material (number of years); for a materials lifespan higher than 50 years (such as concrete, steel reinforcement, timber), the lifetime ratio \( \frac{L_T}{L_i} \) is equal to 1;
- \( Q_i \) represents the quantity of the \( i^{th} \) building material (Table 5-1);
- \( I_i \) is the embodied CO₂-e emissions associated with the \( i^{th} \) building material (kg CO₂-e /unit of material);
- \( C_T \) is related to the truck capacity, which can carry a 20ft container (volume 39 m³);
- \( I_t \) is the embodied CO₂-e emissions associated with the truck used to transport materials (excluding concrete) is assumed as 0.07155 (kg CO₂-e /tonne per km) (Moussavi Nadoushani & Akbarnezhad 2015);
- \( D_i \) is the \( i^{th} \) distance the building material travels from the supplier to the construction site (Kilometres).
Stage 2 of methodology considers the variations associated with the lifetime of materials, embodied CO$_2$-e emissions, and the travel distance. The amount of variation is calculated based on collecting data from published literature to represent the mean and standard deviation values. The variations in the material’s lifespan came from published literature (Cabeza et al. 2014; Ding 2004; Ding 2008; eTool 2014; Furuta et al. 2014; Thormark 2006). The embodied CO$_2$-e emissions coefficient associated with the building materials came from six inventory databases: BPIC (BPIC 2014), ICE (Hammond et al. 2011), eTools (eTool 2014), Alcon (Alcorn 2003), AusLCI (AusLCI 2016), Crawford (2011), and other published literature (Moussavi Nadoushani & Akbarnezhad 2015; Robati et al. 2016). The variations associated with the travel distance from material suppliers to the construction site are estimated by using Google maps (Poinssot et al. 2014). It is assumed that the building in this Chapter is located in the central business district of Sydney.

The spread of random numbers in stage 3 was predetermined by its specified mean and its specified standard deviation from stage 2. A normal distribution is recommended for modelling the variations associated with each input variable because the maximum and minimum CO$_2$-e emissions values were not clear enough to define them (Inyim et al. 2016; Peña-Mora et al. 2009). It was therefore assumed that all the parameters (lifetime, embodied CO$_2$-e emissions and travel distance) associated with the building materials are distributed normally along the standard deviation (SD). So, the lifetime, the embodied CO$_2$-e emissions of materials, and the travel distance between the material suppliers to the construction sites are distributed separately because each variable comes from different sources of data. A normal distribution is used because
when that other distribution (rectangular, triangular) is combined it often yields a net distribution which is close to normal (Farrance & Frenkel 2014).

The quantities of the parameters are related to the materials used in the building, and the quantities of materials used in the building are derived from NS 11401.1 (NS11401.1 2014) as shown in Table 5-1. For the Flat plate, Post-tensioned, and Waffle slab, the estimated quantities of structural materials (concrete and steel reinforcement) are based on a detailed structural analysis where the Excel spreadsheet and JMP (statistical software) (JMP 2017) are used for the uncertainty analysis.
### Table 5-1 Uncertainty of physical parameters

<table>
<thead>
<tr>
<th>Building materials (i)</th>
<th>Unit</th>
<th>Quantity</th>
<th>Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flat slab (F.S.R)</td>
<td>Flat plate (F.P)</td>
<td>Post-tensioned (P.T)</td>
</tr>
<tr>
<td></td>
<td>Lifetime (years)</td>
<td>Embodied CO₂-e emissions (kg/unit of material)</td>
<td>Distance (km)</td>
</tr>
<tr>
<td>------------------------------</td>
<td>-----------------</td>
<td>------------------</td>
<td>----------------------</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
</tr>
<tr>
<td>Concrete</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Concrete on ground</td>
<td>m³</td>
<td></td>
<td>m³</td>
</tr>
<tr>
<td>(N20)</td>
<td>250</td>
<td>250</td>
<td>250</td>
</tr>
<tr>
<td>2 Suspended concrete</td>
<td>m³</td>
<td></td>
<td>m³</td>
</tr>
<tr>
<td>(N32)</td>
<td>2,775</td>
<td>3,005</td>
<td>2,994</td>
</tr>
<tr>
<td>3 Suspended concrete</td>
<td>m³</td>
<td></td>
<td>m³</td>
</tr>
<tr>
<td>(N40)</td>
<td>124</td>
<td>124</td>
<td>124</td>
</tr>
<tr>
<td>Steel reinforcement</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 Steel in concrete</td>
<td>tonnes</td>
<td></td>
<td>tonnes</td>
</tr>
<tr>
<td></td>
<td>411</td>
<td>630</td>
<td>376</td>
</tr>
<tr>
<td>5 Tender</td>
<td>tonnes</td>
<td></td>
<td>tonnes</td>
</tr>
<tr>
<td></td>
<td>95</td>
<td>98</td>
<td>1.22</td>
</tr>
<tr>
<td>Formwork</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 Timber formwork</td>
<td>tonnes</td>
<td></td>
<td>tonnes</td>
</tr>
<tr>
<td></td>
<td>261</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>7 Steel formwork</td>
<td>tonnes</td>
<td></td>
<td>tonnes</td>
</tr>
<tr>
<td></td>
<td>11.16</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>8 Plastic based formwork</td>
<td>tonnes</td>
<td></td>
<td>tonnes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.6</td>
<td></td>
</tr>
<tr>
<td>9 Plastic duct</td>
<td>tonnes</td>
<td></td>
<td>tonnes</td>
</tr>
<tr>
<td></td>
<td>33</td>
<td>14</td>
<td>4.32</td>
</tr>
<tr>
<td>Roof</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 Timber battens</td>
<td>tonnes</td>
<td></td>
<td>tonnes</td>
</tr>
<tr>
<td></td>
<td>20.1</td>
<td>90</td>
<td>1.54</td>
</tr>
<tr>
<td>Roof plumbing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 Steel eaves gutter</td>
<td>tonnes</td>
<td></td>
<td>tonnes</td>
</tr>
<tr>
<td></td>
<td>0.21</td>
<td>100</td>
<td>1.54</td>
</tr>
<tr>
<td>9 Steel ridge flashing</td>
<td>tonnes</td>
<td></td>
<td>tonnes</td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td>100</td>
<td>1.54</td>
</tr>
<tr>
<td>1 Steel fascia</td>
<td>tonnes</td>
<td></td>
<td>tonnes</td>
</tr>
<tr>
<td></td>
<td>0.64</td>
<td>100</td>
<td>1.54</td>
</tr>
<tr>
<td>1 Steel downpipe</td>
<td>tonnes</td>
<td></td>
<td>tonnes</td>
</tr>
<tr>
<td></td>
<td>2.25</td>
<td>100</td>
<td>1.54</td>
</tr>
<tr>
<td>Ceiling and wall lining</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 13 mm plasterboard</td>
<td>tonnes</td>
<td></td>
<td>tonnes</td>
</tr>
<tr>
<td></td>
<td>205.92</td>
<td>33</td>
<td>0.39</td>
</tr>
<tr>
<td>Insulation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Roof and Ceiling insulation: glass wool ceiling batts</td>
<td>tonnes</td>
<td></td>
<td>tonnes</td>
</tr>
<tr>
<td></td>
<td>1.41</td>
<td>60</td>
<td>1.02</td>
</tr>
<tr>
<td>1 Wall insulation: glass wool wall batts</td>
<td>tonnes</td>
<td></td>
<td>tonnes</td>
</tr>
<tr>
<td></td>
<td>3.57</td>
<td>60</td>
<td>1.02</td>
</tr>
<tr>
<td>Vehicular doors</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Steel doors and mechanisms</td>
<td>tonnes</td>
<td></td>
<td>tonnes</td>
</tr>
<tr>
<td></td>
<td>0.18</td>
<td>100</td>
<td>1.95</td>
</tr>
<tr>
<td>Windows, doors and glazing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Glass window (10 mm heat absorbing float glass)</td>
<td>m²</td>
<td></td>
<td>m²</td>
</tr>
<tr>
<td></td>
<td>4320.1</td>
<td>29</td>
<td>189.5</td>
</tr>
</tbody>
</table>

F.S.R: Flat slab for the reference building in proposed span distance of 5.27 m and slab thickness of 185 mm (NS11401.1 2014); F.P: Flat plate in the reference building with span distance of 5.27 m and slab thickness of 200 mm; P.T: Post-tensioned slab in the reference building with span distance of 5.27 m and slab thickness of 175 mm. W.S: Waffle slab in the reference building with span distance of 5.27 m and a slab thickness of 250 mm (50mm topping + 200 stem depth).

a. The High-Density Polyethylene weight was considered as 4.83 kg per each formwork item; b. The Plastic duct weight was assumed as 0.98 kg/m.
5.5 Results and discussion

The Monte Carlo uncertainty analysis represents embodied CO$_2$-e emissions associated with different structural forms. These results are based on 1000 values of each parameter generated independently from normal distributions, with the mean and standard deviations as shown in Table 5-1. The standard deviation is estimated based on the variations associated with the Chapter parameters (lifetime, embodied CO$_2$-e emissions and travel distance). For instance, Figure 5-3 presents the variations associated with the embodied CO$_2$-e emissions coefficients for two grades of concrete (N32 and N40); for concrete N32 and N40, the standard deviation and mean values are obtained from the 203 and 175 datasets, respectively.

![Embodied CO$_2$-e across inventory databases for 32 MPa Concrete](image1)

![Embodied CO$_2$-e across inventory databases for 40 MPa Concrete](image2)

Figure 5-3 Embodied CO$_2$-e emissions variations for two grades of concrete (N32 and N40)
Figure 5-4 summarises the global uncertainties associated with the four different structural systems in this Chapter. Note that there are differences across the spread of data; the Waffle slab and Post-tensioned slab have the lowest mean embodied CO₂-e emissions values compared to the flat plate and Flat slab, for the reference benchmark building. By adding up the embodied CO₂-e emissions of the building materials, the total embodied CO₂-e emissions associated with the proposed benchmark building (shown as F.S.R in Figure 5-4) ranges from 2,106 to 9,664 tonne CO₂-e emissions, with a mean value of 5,185 tonne CO₂-e emissions. The results of different structural forms show that the Flat slab (for reference building benchmark building) has the highest mean embodied CO₂-e emissions due to the thicker slab and higher volume of concrete.
F.S.R: Flat slab for the reference building in proposed span distance of 5.27 m and slab thickness of 185 mm (NS11401.1 2014); F.P: Flat plate in the reference building with span distance of 5.27 m and slab thickness of 200 mm; P.T: Post-tensioned slab in the reference building with span distance of 5.27 m and slab thickness of 175 mm. W.S: Waffle slab in the reference building with span distance of 5.27 m and slab thickness of 250 mm (50mm topping + 200 stem depth).

Figure 5-4 Probability distributions of predicted embodied CO₂-e emissions for the four slabs
The variance associated with environmental impact (embodied CO$_2$-e /m$^2$) of each structural system is shown in Figure 5-5; it shows the small differences between the embodied CO$_2$-e /m$^2$ of the four structural systems. The median embodied CO$_2$-e /m$^2$ of the buildings varies by up to 24% across the design alternatives. Reductions in embodied CO$_2$-e emissions can be achieved in most cases by selecting the Waffle slab systems because Waffle slab provides a lighter and stiffer slab than an equivalent flat plate slab (CC 2016; CCAA 2003). Furthermore, the post-tensioned slab (P.T) reduces the mean embodied CO$_2$-e emissions by 51 kg CO$_2$-e /m$^2$ compared to a flat plate slab. The post-tensioned slab is thinner and has a lower volume of concrete and steel reinforcement compared to a conventionally reinforced slab (F.P and F.S.R). The maximum embodied CO$_2$-e emissions did not vary much between W.S and P.T, although the embodied CO$_2$-e emissions associated with W.S was 2% (equivalent to the 10 Kg CO$_2$-e /m$^2$) higher than the P.T slab.

![Figure 5-5 Embodied CO$_2$-e emissions associated with different structural forms](image)

**Figure 5-5 Embodied CO$_2$-e emissions associated with different structural forms**
The sensitivity analysis quantified the magnitude of the changes in the estimated embodied CO$_2$-e emissions of the building materials (variables) across the global uncertainties. The magnitude of variations associated with each building material was estimated by variations of their embodied CO$_2$-e emissions to the total embodied CO$_2$-e emissions for each 1000 iterations. Figure 5-6 provides the probability associated with the environmental impact (embodied CO$_2$-e emissions) of the materials used in the buildings. The cumulative probability gives a reasonable impression of the overall impact of the variations in embodied CO$_2$-e emissions calculations. Note that the structural materials (Concrete and steel reinforcement) and architectural elements (windows with aluminium frame) account for highest proportions of embodied CO$_2$-e emissions.

Figure 5-6 Probability variation associated with the environmental impact (embodied CO$_2$-e emissions) of the materials used in the designed buildings.

The variations of cumulative probability of the output data show significant variations in the amount of embodied CO$_2$-e emissions associated with types of materials. By
considering all four structural systems, the level of uncertainty associated with different types of concrete ranges from 6% to 78% of the total embodied CO$_2$-e emissions of the building. For example, the statistical distribution of the data associated with concrete (N32) has interquartile ranges between 42% and 59% with a mean value of 51%. Note there is a considerable variation in the level of uncertainty associated with the embodied CO$_2$-e emissions of the double-glazed aluminium framed window, so the amount of uncertainty associated with embodied CO$_2$-e emissions from the double-glazed aluminium window ranged from 16% to 25%, with central tendency mean uncertainty of 20%.

For concrete, steel reinforcement, and aluminium framed windows, the uncertainties are mainly from variations of the embodied CO$_2$-e coefficient proposed by different inventory databases. For instance, the amount of embodied CO$_2$-e emissions for concrete changed from 62 to 562 (kg CO$_2$-e /m$^3$ material) in different inventory databases (eTool 2014; Hammond & Jones 2008; Robati et al. 2016). The CO$_2$-e emissions impact associated with windows was sourced from databases as 216 to 279 (kg CO$_2$-e emissions)/m$^2$ (eTool 2014; Hammond et al. 2011). The previous studies confirm that steel, concrete, and glass are the most intensive sectors in the production of typical Australian office buildings due to the various methods and quantities of materials in the upstream process of production as well as large amount of fossil fuels used in upstream process of concrete (Crawford 2011; Yu et al. 2017).

Regardless of the structural types, the proper selection of concrete and steel reinforcement can have a huge influence on the overall embodied CO$_2$-e emissions of buildings.
In terms of variations in embodied CO\textsubscript{2}-e emissions of concrete, previous studies found that Portland cement is a major source of greenhouse emissions during the production of concrete (Kajaste & Hurme 2016). The concrete industry is addressing some of the concerns about environmental problems by adding or replacing the cement with other components related to high embodied CO\textsubscript{2}-e emissions. Previous studies have shown the results of replacing cement in the concrete with alternative cementitious materials (de Castro & de Brito 2013; Ingrao et al. 2014; Jacoby & Pelisser 2015; Robati et al. 2016). The most commonly used cementitious materials are Ground Granulated Blast Furnace Slag (GGBFS) and coal combustion fly ash. GGBFS is a by-product of iron and steel making and fly ash is a by-product of burning coal, mainly for generating electricity. The production process of fly ash and GGBFS involves less greenhouse gas emissions than ordinary Portland cement (Robati et al. 2016; Van den Heede & De Belie 2012). For the structural design of buildings, substituting a portion of Portland cement with GGBFS could substantially reduce the negative environmental impact of concrete, but the production of GGFS is limited and therefore the effects of further shipping must be considered in the calculation of embodied CO\textsubscript{2}-e emissions.

5.6 Conclusion

A Monte Carlo simulation method has been used to examine and predict the impact of uncertainties on the embodied CO\textsubscript{2}-e emissions of a proposed benchmark building. The probability distributions of the most effective building materials (input data) were obtained to estimate the mean (expected) embodied CO\textsubscript{2}-e emissions value associated with each of the structural design systems. The results highlight the contribution and variation of each construction material and structural system from the extraction of
raw materials to the construction site and end of life building. The differences between
the embodied CO2-e emissions of different structural systems are not significant. The
Waffle slab (W.S) has the lowest amount of embodied CO2-e emissions per floor area
and the Flat plate (F.P) system has the highest amount of CO2-e /m². However, once
a structural frame has been chosen, there are significant opportunities for reducing the
CO2-e emissions impact of the building by optimising the quantities of structural
materials (concrete and steel reinforcement). Concrete, double glazed windows with
an aluminium frame and steel reinforcement have the maximum proportion of
embodied CO2-e emissions over a 50-year lifetime of a building. The maximum
percentage contributed by suspended concrete (N32 used for flooring), windows and
steel reinforcement on the overall embodied CO2-e emissions of designed building
structures as high as 78%, 57%, 48%, respectively. An important reason for the
variations in these results is the inconsistency in the inventory of data. The results of
this Chapter can be used as a guideline and reference point for future comparisons of
the environmental impact associated with buildings, materials, and systems. The
potential impact of the structural system on the operational energy and whole life
environmental costs is addressed in Chapter 6 and Chapter 7, respectively.
Chapter 6

Impact of structural design solutions on the energy and thermal performance of an Australian office building

Contribution of the candidate to the Published Work

The contribution of the candidate in the published paper was 90%. He co-authored them with his main and co-supervisors. The candidate modelled, simulated a case study building for energy analysis and wrote the paper. Other authors reviewed the papers and provided useful feedback for improvement.

Citation: Published

6.1 Introduction

The previous Chapter used Monte Carlo analysis to quantify the uncertainties associated with calculating the CO2-e emissions from extracting and transport raw materials to the construction site and end of life activities. This current Chapter investigates the impact of selecting structural materials (Normal weight and Ultra-lightweight concrete) and construction forms during the operational phase of a building.

Concrete is a heavyweight construction material whose high thermal mass could increase the thermal storage capacity of a building envelope and in turn affect indoor thermal comfort. Selecting an appropriate method for concrete construction and form could also affect the total energy performance and thermal comfort of a building, a fact that is often overlooked by structural engineers. This Chapter presents the results of energy simulations of the potential impact that concrete construction forms and structural materials have on the energy consumption of archetypal commercial office buildings in five major Australian cities (Sydney, Melbourne, Canberra, Brisbane and Darwin). This Chapter has three stages: 1) a structural analysis of two construction forms (Flat and Waffle slab); 2) the selection of two types of structural concrete (conventional Normal weight concrete and novel Ultra-lightweight concrete); 3) a comparative analysis to quantify the magnitude of the change in predicted annual energy consumption due to changes in the form of construction and the type of structural concrete. This Chapter provides the underlying approach and results of the first simulation-based assessment that ULWC has on the energy and indoor comfort of commercial buildings.
6.2 The role of structural design in the energy performance of buildings

The structural design of buildings is traditionally limited to material specifications and structural efficiency, whereas structural engineering research often attempts to provide structural efficiency by reducing the materials and resources used while increasing the longevity of structures through design. However, with the aim of continuous innovation in the structural design of buildings, a new model provides a framework to integrate the long-term effects of materials and systems into the design process; indeed, modern integrated structural design could utilise life cycle assessment tools to determine the whole life environmental performance of building design because life cycle energy assessments promote a more efficient use of materials and energy.

The appropriate choice of construction and building materials can potentially reduce the life cycle energy of buildings because materials with low thermal conductivity help to reduce the demand for energy as well as the associated greenhouse gases (GHG) (Torgal & Jalali 2011). For instance, concrete is one of the main construction materials with the ability to absorb and retain energy for a long period of time; action that reduces energy consumption by storing heat in a natural daily cycle (thermal mass). The mass components reduce temperature fluctuations in building spaces and thus reduce the associated peak heating or cooling loads (Torgal & Jalali 2011). Previous studies indicate that the thermal conductivity of concrete varies across Normal, Lightweight, and Ultra-lightweight concrete (Marinkovic et al. 2010; Robati et al. 2016; Wu et al. 2015; Yun et al. 2013; Zhang & Poon 2015); this variation in density stems from changes in the proportion and type of aggregates, and the cementitious materials in the concrete mixture.
Normal weight concrete with a density between 2,200 to 2,600 kg/m$^3$ includes cement, normal weight aggregates, and water, whereas lightweight concrete (1,350 to 1,900 kg/m$^3$) is produced by replacing some of the solid materials in the mix with air voids (Neville 2012). There are three possible locations for the air voids, inside the particles of aggregate, inside the cement paste, and between the coarse aggregate particles (Neville 2012). The potential for substituting ordinary Portland cement with geopolymer materials in Lightweight concrete has been studied extensively by researchers (Abdullah et al. 2012; Robati et al. 2016). Geopolymer concrete is synthesised by mixing aluminosilicate material, alkali solutions, and water (Nuaklong et al. 2016). Also, the potential use of Lightweight hollow spheres in the design mix is a technique for producing Ultra-lightweight concrete (1,154 to 1,471 kg/m$^3$); in fact, ultra-lightweight concrete consists mainly of lightweight hollow spheres (cenosphere materials), water, and a binder (it also includes silica fume and Portland cement) (Robati et al. 2016; Wu et al. 2015).

The thermal properties of a concrete mix are influenced by the thermal properties of ingredients such as cement, aggregates, and the moisture existing in the mix (ACI122R 2014). The replacement of normal aggregate with lightweight aggregates reduces the density and thermal conductivity of concrete. A brief review of previously published values (Table 6-1) shows that the estimated thermal conductivity of Normal, Lightweight, and Ultra-lightweight concrete could vary from 3.1 W/mK to 0.28 W/mK (Berndt 2015; CCAA 2015; Damdelen et al. 2015; Marinkovic et al. 2010; O'Moore & O'Brien 2009; Robati et al. 2016; Tošić et al. 2015; Wu et al. 2015; Yun et al. 2013; Zhang & Poon 2015).
Table 6-1 Thermo-physical and structural properties of concrete classes as reported in the literature

<table>
<thead>
<tr>
<th>References</th>
<th>Density (kg/m³)</th>
<th>Compressive strength (MPa)</th>
<th>Thermal conductivity (W/mK)</th>
<th>Type of concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wu et al. (2015)</td>
<td>966 – 2,251</td>
<td>33 – 69.4</td>
<td>0.28 – 1.98</td>
<td>Normal, Lightweight and Ultra-Lightweight</td>
</tr>
<tr>
<td>Blanco et al. (2000)</td>
<td>1,090 – 1,510</td>
<td>5.04 – 33.03</td>
<td>0.46 – 0.69</td>
<td>Lightweight</td>
</tr>
<tr>
<td>Uysal et al. (2004)</td>
<td>1,329 – 2,270</td>
<td>NA</td>
<td>0.77 – 1.45</td>
<td>Normal and Lightweight</td>
</tr>
<tr>
<td>Topçu and Uygunoğlu (2007)</td>
<td>880* – 1,500</td>
<td>3* – 9*</td>
<td>0.13 – 0.52</td>
<td>Lightweight</td>
</tr>
<tr>
<td>Gül et al. (2007)</td>
<td>1,773 – 1,984</td>
<td>11.3 – 25.1</td>
<td>0.81 – 1.22</td>
<td>Lightweight</td>
</tr>
<tr>
<td>Mounanga et al. (2008)</td>
<td>728 – 2,109</td>
<td>1.4 – 24.3</td>
<td>0.22 – 1.49</td>
<td>Lightweight</td>
</tr>
<tr>
<td>Tandiroğlu (2010)</td>
<td>1,798 – 1,883</td>
<td>60 – 80</td>
<td>1.46* – 1.76*</td>
<td>Lightweight</td>
</tr>
<tr>
<td>Sengul et al. (2011)</td>
<td>392 – 1,937</td>
<td>0.1 – 28.8</td>
<td>0.13 – 0.6</td>
<td>Lightweight</td>
</tr>
<tr>
<td>Kim et al. (2012)</td>
<td>1200* – 2,350*</td>
<td>9* – 40*</td>
<td>0.32* – 0.72*</td>
<td>Normal and Lightweight</td>
</tr>
<tr>
<td>Wang and Meyer (2012)</td>
<td>1560-1980</td>
<td>18*-36.5*</td>
<td>0.27 – 0.61</td>
<td>Lightweight</td>
</tr>
<tr>
<td>Huang et al. (2013)</td>
<td>1649 -2001</td>
<td>23.33* – 48*</td>
<td>0.29 – 0.37</td>
<td>Lightweight</td>
</tr>
<tr>
<td>Yu et al. (2013)</td>
<td>1280 - 1490</td>
<td>23.3 – 27.5</td>
<td>0.49 – 0.85</td>
<td>Lightweight</td>
</tr>
<tr>
<td>Gao et al. (2014)</td>
<td>950* - 2,063*</td>
<td>7.67* – 62.78*</td>
<td>0.23* – 1.97*</td>
<td>Normal and Lightweight</td>
</tr>
<tr>
<td>Yun et al. (2013)</td>
<td>17,44 – 2,370</td>
<td>23 – 43.9</td>
<td>1.30* – 2.25*</td>
<td>Normal and Lightweight</td>
</tr>
</tbody>
</table>

*Extracted from graphs

These studies find that lower density concrete has a lower thermal conductivity, so modern concrete such as Lightweight and Ultra-lightweight concrete has better thermal buffering than traditional concrete (Normal weight concrete), as shown in Figure 6-1.
Several other studies have shown that buildings with a high thermal mass require more time to heat up and cool down, which might influence thermal comfort and demand more energy for heating and cooling (Hoes et al. 2011; Roberz et al. 2017).

Moreover, the ongoing development of more novel construction materials such as Ultra-lightweight concrete (Huiskes et al. 2016; Roberz et al. 2017; Yu, QL et al. 2015) raises a question about their potential impact on the thermal mass of a building and hence on the overall energy performance of a real building during its operational phase.

Therefore, the primary objective of this Chapter is to indicate how the selection of concrete as a construction material affects the overall energy performance of a building. This Chapter explores a benchmarking method to evaluate the potential effects of conventional (Normal weight) and novel concrete materials (Ultra-lightweight) on the thermal performance of typical office buildings in Australia. A benchmark building serves as a framework to compare design alternatives in terms of...
their energy performance. The benchmarking system in this study considers the different climate zones in Australia, the forms of construction (Flat and Waffle slabs), and the structural materials (conventional and novel concrete).

This research is organised as follows. Section 6.3 summarises the method used to design the structure and simulate the thermal performance of the benchmark office building. Section 6.4.1 provides the structural design and analysis results; Sections 6.4.2 and 6.4.3 compare the results of the energy performance for different structural materials and construction forms, and Section 6.5 reports the key findings of this Chapter.

6.3 Methodology

6.3.1 Description of base building

This Chapter assesses the thermal performance of concrete materials (Normal weight and Ultra-lightweight concrete) and structural forms (lightweight and heavyweight) for a benchmark office building in Australia. This 15 storey office building is one of four benchmarking buildings proposed by the National Standard Organization (NSDO) in Australia (NS11401.1 2014); This particular 15 storey office building is a typical concrete structure (NS11401.1 2014), with a square plan shape, a total floor area of 1000m², and an average 3.3 m height per storey, as shown in Table 6-2.
### Table 6-2 Overall specifications of the benchmark building

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basement dimensions</td>
<td>m</td>
<td>31.62 × 31.62</td>
</tr>
<tr>
<td>Number of Stories</td>
<td>---</td>
<td>15</td>
</tr>
<tr>
<td>Concrete slab on ground</td>
<td>mm</td>
<td>200</td>
</tr>
<tr>
<td>Concrete suspended slab</td>
<td>mm</td>
<td>175</td>
</tr>
<tr>
<td>Average elevation per floor</td>
<td>m</td>
<td>3.3</td>
</tr>
<tr>
<td>Total floor Area (including parking, Stairs &amp; Verandas)</td>
<td>m²</td>
<td>15,000</td>
</tr>
<tr>
<td>Total habitable area (external dimensions)</td>
<td>m²</td>
<td>8,807.1</td>
</tr>
<tr>
<td>Total habitable area (internal dimensions)</td>
<td>m²</td>
<td>962.4</td>
</tr>
<tr>
<td>No of floors above ground level</td>
<td>---</td>
<td>11</td>
</tr>
<tr>
<td>No of rooms</td>
<td>---</td>
<td>176</td>
</tr>
</tbody>
</table>

This building has two parts; the first three underground storeys are parking and storage areas, while the remaining twelve storeys are open plan office areas. The building has non-openable windows, with a thermal transmittance (U value) for the base case of 5.7 W/m²K and a Solar Heat Gain Coefficient of 0.6 (BZE 2013). A sketch of this office building is shown in Figures 6-2 and 6-3.
6.3.2 Structural design parameters

In terms of structural analysis and design, a concrete structure design is considered to account for lightweight and heavyweight structures if they follow the Australian Standards Concrete structures (AS3600 2009); the lightweight structure is designed as a Waffle slab and the heavyweight structure is based on a Flat slab. Flat slabs are very adaptable elements that are generally used to provide minimum depth and flexible column grids in construction, whereas Waffle slabs are a lighter and stiffer slab than the equivalent Flat slab. A Waffle slab has a thin topping and narrow ribs spanning in both directions between the column heads and/or beam band. The strength and serviceability aspects of the code were utilised during the design of this building. The process for structural analysis is summarised in Figure 6-4.
The amount of live load comes from the Australian and New Zealand Standard for imposed actions (AS/NZ1170.0 2002). The live load for the office storage and parking areas was 5kPa and 3kPa for the work rooms. The dead load for concrete elements (columns, shear walls, slabs and staircase) was obtained by multiplying the volume of the member by the unit weight of concrete. Wind loads on the building were determined in accordance with Australian and New Zealand standard wind actions (AS/NZ1170.2 2011). The magnitude of wind pressure on the structure was calculated based on its height above ground, its size, importance, and location. The level of importance is level 3, because the consequence of failure is deemed to be high (based on AS/NZ1170.0 2002).
on occupancy and by using AS 1170 (AS/NZ1170.0 2002)). For ultimate limit states and structural serviceability, the annual probability exceedance comes from AS 1170 (AS/NZ1170.0 2002), table 3.1 for a design working life of 50 years in a cyclone zone in Australia. To calculate the wind load, zone D was considered to be enough strength in the structure as well as validating the practicality of building in other zones. With the loading conditions, a combinations of action loads were used to check the serviceability and strength of the building in accordance with clause 4.2.1 and 4.2.2 of the AS1170 (AS/NZ1170.0 2002), as shown in Table 6-3. The Computer Aid Design package Etabs, Safe and Microsoft Excel spreadsheet were used to verify the minimum requirements of the concrete design code. A summary of the structural analysis is shown in Appendix B.

### Table 6-3 Loading conditions for design the building

<table>
<thead>
<tr>
<th>Type of load</th>
<th>Load (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Live load-Office storage and parking area</td>
<td>5</td>
</tr>
<tr>
<td>Live load-Work rooms</td>
<td>3</td>
</tr>
<tr>
<td>Dead Load</td>
<td>4.3</td>
</tr>
<tr>
<td>Wind Load- Windward</td>
<td>Ultimate limit states 6.6</td>
</tr>
<tr>
<td></td>
<td>Serviceability limit states 5.4</td>
</tr>
<tr>
<td>Wind Load- Leeward</td>
<td>Ultimate limit states 4.1</td>
</tr>
<tr>
<td></td>
<td>Serviceability limit states 3.4</td>
</tr>
<tr>
<td>Wind Load- Sidewall</td>
<td>Ultimate limit states 1.3</td>
</tr>
<tr>
<td></td>
<td>Serviceability limit states 1.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Load combinations for Ultimate state design</th>
<th>Load combinations for serviceability state design</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.35G</td>
<td>G+ Ψl Q</td>
</tr>
<tr>
<td>1.25G+1.5Q</td>
<td>G+ Ψs Q</td>
</tr>
<tr>
<td>1.25G+1.5ΨlQ</td>
<td>G+ ΨsQ + Ws</td>
</tr>
<tr>
<td>1.2G+Wu+ΨcQ</td>
<td></td>
</tr>
<tr>
<td>0.9G+Wu</td>
<td></td>
</tr>
</tbody>
</table>

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

This Chapter analyses the effects choices of concrete (normal and low-density) have on the thermal performance of a heavyweight and lightweight office structure. For the purpose of this Chapter, the types of concrete mixes were collected from previously published journal papers and databases (CCAA 2015; O'Moore & O'Brien 2009; Wu et al. 2015; Yun et al. 2013). These designs represent conventional (Normal weight) and some advanced methods of concrete admixture that give Ultra-lightweight concrete. Table 6-4 summarises the properties and grade of the concrete analysed in this Chapter. Novel forms of concrete admixture (such as Ultra-lightweight) are included in this Chapter to point out their potential effects on the thermal impacts of the building; they have not yet been covered in the mainstream of previous studies.

Table 6-4 Properties of selected concrete

<table>
<thead>
<tr>
<th>Type of Concrete</th>
<th>Grade (MPa)</th>
<th>Density (Kg/m³)</th>
<th>Thermal conductivity (W/mK)</th>
<th>Specific heat kJ/(kg.k)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>N40- Normal weight</td>
<td>40</td>
<td>2393</td>
<td>1.96</td>
<td>0.88</td>
<td>(CCAA 2015)</td>
</tr>
<tr>
<td>N40- Ultra-lightweight</td>
<td>40</td>
<td>1400</td>
<td>0.31</td>
<td>0.88</td>
<td>(Wu et al. 2015)</td>
</tr>
<tr>
<td>N32- Normal weight</td>
<td>32</td>
<td>2470</td>
<td>2.10</td>
<td>0.88</td>
<td>(O'Moore &amp; O'Brien 2009)</td>
</tr>
<tr>
<td>N32- Ultra-lightweight</td>
<td>32</td>
<td>1164</td>
<td>0.28</td>
<td>0.88</td>
<td>(Wu et al. 2015)</td>
</tr>
<tr>
<td>N20- Normal weight</td>
<td>20</td>
<td>1483</td>
<td>1.38</td>
<td>0.88</td>
<td>(Yun et al. 2013)</td>
</tr>
</tbody>
</table>

1. Grade N40 used in the vertical structural elements such as columns and shear walls.
2. Grade N32 used in the slabs (Waffle and Flat).
3. Grade N20 used in the other concrete element (staircase).

6.3.4 Operational energy analysis

Heavyweight (Flat slab) and lightweight (Waffle slab) structures were modelled and compared for their impact on the energy performance of the building by using the DesignBuilder energy simulation software. DesignBuilder is a user interface for the
EnergyPlus dynamic thermal simulation engine and requires hourly weather data as inputs. The weather data used for each city in this Chapter was extracted from the EnergyPlus weather database (EnergyPlus 2017). The weather data are in RMY format, they are a set of weather files developed to comply with the Building Code of Australia (EnergyPlus 2017).

The equipment and occupancy schedules were extracted from the Building Code of Australia (ABCB 2015). The schedules assume 10% of office equipment and 10% of lights remain on during unoccupied hours. The HVAC system was modelled using a variable air volume system (VAV) with the autosize routine in DesignBuilder’s “simple” HVAC description (DesignBuilder 2017). Table 6-5 summarises the main assumptions used for the simulations.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Key variables</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lighting power density</td>
<td>9 (W/m²)</td>
<td>(ABCB 2015)</td>
</tr>
<tr>
<td>Occupancy density</td>
<td>10 (m²/person)</td>
<td>(ABCB 2015)</td>
</tr>
<tr>
<td>Equipment load</td>
<td>15 (W/m²)</td>
<td>(ABCB 2015)</td>
</tr>
<tr>
<td>Domestic hot water</td>
<td>0.4 (L/m²)</td>
<td>(ABCB 2015)</td>
</tr>
<tr>
<td>Infiltration</td>
<td>0.28 (ACH)</td>
<td>(Egan 2011)</td>
</tr>
<tr>
<td>Ventilation requirements</td>
<td>10 (L/s/person)</td>
<td>(ABCB 2015)</td>
</tr>
<tr>
<td>HVAC set point</td>
<td>18°C (heating) - 26°C (cooling)</td>
<td>(ABCB 2015)</td>
</tr>
</tbody>
</table>

*The schedules were extracted from Building Code of Australia (ABCB 2015)

This Chapter used the Building Code of Australia (BCA) “deemed to satisfy” approach to define the envelope construction of the modelled building (as shown in Table 6-6).

To understand the relative magnitude of the change in predicting energy consumption due to changes in the form of construction and type of structural concrete, the office building was modelled in four different ways: 1) as a Flat slab with Normal weight;
2) as a Flat slab with Ultra-lightweight concrete; 3) a Waffle slab with Normal weight concrete; and 4) a Waffle slab with Ultra-lightweight concrete. The vertical elements (columns and shear walls) consist of concrete with grade N40, the slabs (Waffle and Flat) contain N32 and the other elements (staircase) are made of N20. The modelling results for all four buildings revealed the total energy usage as well as the heating and cooling loads across different input parameters (design alternatives). The total energy consumption was compared to national and state averages determined from real world data from Australian office buildings to ensure the results are within reasonable ranges of the published and predicted energy consumption values (Pitt & Sherry 2012).

**Table 6-6 Physical properties of benchmark building**

<table>
<thead>
<tr>
<th>Elements</th>
<th>R-values (m².K/W)</th>
<th>Item description</th>
<th>References</th>
</tr>
</thead>
</table>
| Ground floor      | 1.25             | 1. Indoor air film (still air)  
2. Solid concrete (150 mm, 2400 kg/m³)  
3. Ground thermal resistance | (ABCB 2015)         |
| Intermediate floors | a. 1.25  
b. 1.81  
c. 1.22  
d. 1.63 | 1. Indoor air film (still air)  
2. Solid concrete (Study parameters)  
a. Flat with Normal weight concrete  
b. Flat with Ultra-lightweight concrete  
c. Waffle slab with Normal weight concrete  
d. Waffle slab with Ultra-lightweight concrete  
3. Outdoor air film (7 m/s) | (ABCB 2015)         |
| Roof              | a. 4.20  
b. 4.84  
c. 4.17  
d. 4.58 | 1. Outdoor air film  
2. Roof Water Proofing Membrane  
3. Solid concrete, (Study parameters)  
a. Flat with Normal weight concrete  
b. Flat with Ultra-lightweight concrete  
c. Waffle slab with Normal weight concrete  
d. Waffle slab with Ultra-lightweight concrete  
4.5. Reflective Insulation Material R value  
6. Reflective Air Space | Based on BCA requirements (ICANZ 2010) |
### 6.4 Results and discussion

#### 6.4.1 Structural analysis and design

The office benchmark building has been structurally designed based on Australian Standards in order to verify whether it can be used for realistic comparisons. The structural design specified heavyweight and lightweight alternatives for the Flat slab and Waffle slab construction. The structural analysis and design quantified the minimum size of the slab and column for each form of construction. The columns were classified into five (5) different groups based on their cross section and reinforcement details (Appendix B). The columns at the lower level have a larger cross sectional area and a higher ratio of steel than the upper columns. The dynamic lateral forces (earthquake) are excluded from the scope of this Chapter because the wind pressure loads are much more critical than earthquakes in most parts of Australia. The structural design is summarised in Table 6-7 (the structural design is shown in Appendix B).
Table 6-7 Summary of the structural design

<table>
<thead>
<tr>
<th>Construction form</th>
<th>Flat slab</th>
<th>Waffle slab</th>
</tr>
</thead>
<tbody>
<tr>
<td>Column span distance (L)</td>
<td>5.27 m</td>
<td>5.27 m</td>
</tr>
<tr>
<td>Slab thickness (D)</td>
<td>200 mm</td>
<td>250 mm</td>
</tr>
<tr>
<td>Concrete quantities (m$^3$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N20</td>
<td>250</td>
<td>250</td>
</tr>
<tr>
<td>N32</td>
<td>3,005</td>
<td>2,002</td>
</tr>
<tr>
<td>N40</td>
<td>124</td>
<td>124</td>
</tr>
<tr>
<td>Steel quantities (Tonne)</td>
<td>753</td>
<td>679</td>
</tr>
<tr>
<td>Cross section</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

6.4.2 Energy performance of the building (Energy consumption)

Five major locations were selected for five major Australian cities and the heating and cooling hours are shown in Figure 6-5. The heating and cooling hours are calculated based on the differences between the outside weather temperature and a reference temperature which considered less than 18 degrees Celsius for heating and more than 24 degrees Celsius for cooling (BOM 2011). Darwin is located in climate zone 1, so it has a perennially hot climate with the highest number of cooling hours (Hot humid summer & warm winter). Brisbane has the second highest cooling degree hours and is (climate zone 2) having a subtropical climate with warm, humid summers and mild winters. Sydney’s climate is influenced by abundant sunshine over the summer and a mild winter (climate zone 5) that results in higher heating degree hours than Brisbane. Melbourne and Canberra have high heating demand compared to the other cities. Melbourne has a temperate climate with changeable weather conditions in the spring and summer seasons (climate zone 6). Canberra is a cool temperate climate zone, with the highest heating degree hours over a year of the five climates examined in this Chapter.
Climate zones: Darwin (1); Brisbane (2); Sydney (5); Melbourne (6); Canberra (7)

Figure 6-5 Summary of the annual heating and cooling degree-hours

The simulated annual energy consumption is compared and verified with the average national energy usage across the five major climate zones, as shown in Figure 6-6. The Australian national average for commercial building energy consumption is 272±17 [kWh/m²], with a standard deviation of 128 [kWh/m²] per year (Bannister 2004; Daly et al. 2014), and the simulated outputs from this Chapter are within these ranges. The results of the simulated building energy performance showed that in this type of highly glazed office buildings, the cooling load is much higher than the heating load across all five climates studied.
**Waffle.low**: lightweight structure (Waffle slab) with Ultra-lightweight concrete; **Waffle.normal**: lightweight structure (Waffle slab) with Normal weight concrete; **200.low**: heavyweight structure (200mm Flat slab) with Ultra-lightweight concrete; **200.normal**: heavyweight structure (200mm Flat slab) with Normal weight concrete.

**Figure 6-6 Predicted annual energy consumptions and national energy average usage across five major climate zones**

The energy consumption across all five climates shows that the lightweight office building (called Waffle.low) with a lower thermal conductivity concrete (Ultra-lightweight concrete) demanded more energy than the other buildings because its fast response to temperature and heat flux excitations caused it to overheat for most of the year. The energy consumption predicted for the heavier type of office building (Flat slab using Normal weight concrete) was consistently lower than the buildings with Ultra-lightweight concrete (Waffle.low and 200.low). Figure 6-7 shows a comparison between the cooling energy requirements of the building with different constructions (Flat and Waffle slab) and different types of concrete. Note that the cooling energy requirements of the buildings were affected by the quantity (lightweight and heavyweight structure) and type of concrete (Normal weight and Ultra-lightweight) used in the building. Ultra-lightweight concrete had a greater effect on the demand for
cooling energy than for colder climates; for example, the office buildings with Ultra-lightweight concrete in Melbourne demanded up to 14% more cooling energy than the heavyweight structure (Flat slab) with Normal weight concrete.

When Normal weight concrete was used there was no great difference between the demand for cooling energy by buildings with heavyweight and lightweight structures. However, the simulations for the building with Ultra-lightweight concrete showed that the cooling energy needed by the heavyweight structure (200.low - Flat slab) were less than the lightweight structure (Waffle.low - Waffle slab) across all five climates, albeit the differences were only between 2-3 kWh/m² per annum.

**Figure 6-7 Comparison between the annual energy requirements, structural forms and construction materials of the office buildings**
6.4.3 Analysis of thermal performance

The results of sub-hourly dynamic simulations were analysed with no active heating/cooling system being used (free-floating conditions) in order to compare the effects of the different building models in terms of indoor temperature during the summer and winter seasons. To reduce the quantity of data for this Chapter, representative periods taken from the set of simulations were analysed with reference to winter and summer seasons (as shown in Table 6-8). In Australia, the summer and winter seasons are defined from December to February (for climate zone 1, the hottest season starts from mid-November) and June to August, respectively.

Table 6-8 Summer and Winter design weeks for the climate zones (DesignBuilder 2017)

<table>
<thead>
<tr>
<th>City (Climate Zone)</th>
<th>Winter design week</th>
<th>Summer design week</th>
</tr>
</thead>
<tbody>
<tr>
<td>Darwin (1)</td>
<td>10 to 16 Jun</td>
<td>19 to 25 November</td>
</tr>
<tr>
<td>Brisbane (2)</td>
<td>3 to 9 August</td>
<td>17 to 23 February</td>
</tr>
<tr>
<td>Sydney (5)</td>
<td>20 to 26 July</td>
<td>3 to 9 February</td>
</tr>
<tr>
<td>Melbourne (6)</td>
<td>6 to 12 July</td>
<td>27 January to 2 February</td>
</tr>
<tr>
<td>Canberra (7)</td>
<td>8 to 15 July</td>
<td>1 to 8 January</td>
</tr>
</tbody>
</table>

The indoor air temperature simulated hourly for the top floor was plotted against the hourly outdoor temperature to compare the indoor thermal performance across the different types of construction (as shown in Figure 6-8 and Appendix C). Indoor air temperatures were plotted against outdoor air temperatures for all four types of construction types, and show that those buildings with Normal weight concrete had a lower slope of regression in response to fluctuations in the outdoor air temperature,
whereas the buildings with Ultra-lightweight concrete had a higher regression coefficient.

<table>
<thead>
<tr>
<th></th>
<th>Summer</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y = 4.874 + 1.194*X</td>
<td>Y = -16.81 + 0.6768*X</td>
<td></td>
</tr>
<tr>
<td>Y = 7.303 + 1.087*X</td>
<td>Y = 17.85 + 0.5966*X</td>
<td></td>
</tr>
<tr>
<td>Y = 4.962 + 1.188*X</td>
<td>Y = -16.85 + 0.6756*X</td>
<td></td>
</tr>
<tr>
<td>Y = 7.481 + 1.078*X</td>
<td>Y = 17.95 + 0.5926*X</td>
<td></td>
</tr>
</tbody>
</table>

Figure 6-8 Hourly air room temperature plotted against the hourly outdoor temperate for the Waffle.low and 200.normal in the climate zone 2 (Brisbane).

The hourly free floating analysis for the buildings with selected constructions shows how the structural mass and type of concrete affected the daily peak indoor temperatures. Table 6-9 summarises the differences in the peak daily indoor air temperature between the highest and lowest structural mass and concrete density.
(200.normal and Waffle.low, respectively). Note that the peak indoor temperatures are higher in those building with Ultra-lightweight concrete and lower structural mass (Waffle.low). For instance, the mean differences in the peak indoor air temperature between the Waffle.low and 200.normal cases (both located in climate 2) in summer and winter are 1.1 and 1.0°C respectively.

Table 6-9 Differences in the peak daily indoor air temperature between Waffle.low and 200.normal

<table>
<thead>
<tr>
<th>Year</th>
<th>Summer season</th>
<th>Winter season</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Annual mean of peak daily indoor air temperature difference [°C]</td>
<td>Number of Samples (days)</td>
</tr>
<tr>
<td></td>
<td>Standard Deviation</td>
<td></td>
</tr>
<tr>
<td>Canberra</td>
<td>0.9</td>
<td>0.64</td>
</tr>
<tr>
<td>Melbourne</td>
<td>0.8</td>
<td>0.75</td>
</tr>
<tr>
<td>Sydney</td>
<td>1.0</td>
<td>0.75</td>
</tr>
<tr>
<td>Brisbane</td>
<td>1.0</td>
<td>0.75</td>
</tr>
<tr>
<td>Darwin</td>
<td>1.0</td>
<td>0.75</td>
</tr>
</tbody>
</table>
Figures 6-9 to 6-13 show the hourly indoor air temperatures during the summer and winter seasons; note that the building with a lower structural mass (thermal mass) and lower concrete density (Ultra-lightweight) is more sensitive to changes in the outdoor temperatures.

* Indoor temperature (200 normal) [°C]  +  Indoor temperature (Ultra-light) [°C]  —  Average Indoor temperature (200 normal) [°C]  —  Average Indoor temperature (Ultra-light) [°C]

**Figure 6-9 Summer and Winter free floating temperature in climate zone 1 (Darwin)**

**Figure 6-10 Summer and Winter free floating temperature in climate zone 2 (Brisbane)**

**Figure 6-11 Summer and Winter free floating temperature in climate zone 5 (Sydney)**
Figure 6-12 Summer and Winter free floating temperature in climate zone 6 (Melbourne)

Figure 6-13 Summer and Winter free floating temperature in climate zone 7 (Canberra)

6.4.4 Design week-free floating analysis

Figure 6-14 plots the frequency of indoor air temperature during the summer and winter design weeks by considering the heavyweight building with Normal concrete (200.normal) and the lightweight building with Ultra-lightweight concrete (Waffle.low); the indoor air temperature of both buildings and across all climates was outside the desired air setpoint ranges (18 to 26°C) most of the time, accompanied by consistent overheating (air temperatures higher than 26°C).
Figure 6-14 Probability of indoor air temperature during the summer and winter design weeks for 200.normal and Waffle.low
Those structures with higher thermal conductivity concrete (200.normal) had lower peak indoor air temperatures than the low thermal conductivity concrete structures (Waffle.low); for example, the variations of indoor and outdoor air temperature for the designed buildings in two climate zones (1 and 6) during the winter design week are shown in Figure 6-15. They indicate that the concrete structure with a lower thermal conductivity had a substantial increase of peak indoor air temperature by 1.2°C and 2°C in hot and cold climate zones, respectively (as shown in Figure 6-15 and in Appendix D).

![Graph of Winter design week temperature outlook](image)

**Figure 6-15 Analysis of Winter design week free-floating for climate zones 1 (Darwin) and 6 (Melbourne)**

In the summer design week, the resulting temperature patterns show that lighter buildings characterised by Ultra-lightweight concrete (Waffle.low) experienced a
higher daily oscillation than the other types of construction (as shown in Figure 6-16 and in Appendix D), where the building with higher mass and Normal weight concrete (200.normal) structures had lower indoor air temperatures in general and a peak indoor air temperature that was 1.6-2.4°C lower than the lighter construction types. However, those structures in the hot dominated climate zone (Darwin) built with Ultra-lightweight materials lost heat quickly and cooled down faster during the night than the other buildings.

![Diagram showing temperature trends](image)

**Figure 6-16 Analysis of Summer design week free-floating for climate zones 2 (Brisbane) and 7 (Canberra)**

Table 6-10 shows the indoor thermal comfort conditions during operative hours (7 am to 9 pm) in the summer and winter design week. The accumulated degrees Celsius by which the hourly indoor air temperature was higher or lower than the desired comfort temperature (26 and 18°C, respectively in this case) is defined here as discomfort degree hours (DDH) (Ferrari & Zanotto 2015). The results here show that the DDH were almost 5% higher in the building constructed from Ultra-lightweight concrete.
across all climates during the summer design week. The heavy buildings with Normal weight concrete reached a lower DDH (up to 50%) than the Ultra-lightweight concrete in cold climates (zones 6 and 7) during the winter design week. Note that those buildings with same type of concrete had a similar performance during the summer and winter design weeks.

Table 6-10 Summary of discomfort degree hours during the design weeks

<table>
<thead>
<tr>
<th>Major cities (climate)</th>
<th>Summer design week</th>
<th>Winter design week</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>200.normal</td>
<td>Waffle.normal</td>
</tr>
<tr>
<td></td>
<td>200.low</td>
<td>Waffle.low</td>
</tr>
<tr>
<td>Canberra (7)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N.DDH</td>
<td>112</td>
<td>112</td>
</tr>
<tr>
<td>DDH</td>
<td>1,033</td>
<td>1,064</td>
</tr>
<tr>
<td>M.DDH</td>
<td>5.44</td>
<td>5.60</td>
</tr>
<tr>
<td>Melbourne (6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N.DDH</td>
<td>98</td>
<td>97</td>
</tr>
<tr>
<td>DDH</td>
<td>645</td>
<td>660</td>
</tr>
<tr>
<td>M.DDH</td>
<td>3.84</td>
<td>3.93</td>
</tr>
<tr>
<td>Sydney (5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N.DDH</td>
<td>98</td>
<td>98</td>
</tr>
<tr>
<td>DDH</td>
<td>1,257</td>
<td>1,295</td>
</tr>
<tr>
<td>M.DDH</td>
<td>7.48</td>
<td>7.71</td>
</tr>
<tr>
<td>Brisbane (2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N.DDH</td>
<td>98</td>
<td>98</td>
</tr>
<tr>
<td>DDH</td>
<td>982</td>
<td>1,008</td>
</tr>
<tr>
<td>M.DDH</td>
<td>5.85</td>
<td>6.00</td>
</tr>
<tr>
<td>Darwin (1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N.DDH</td>
<td>98</td>
<td>98</td>
</tr>
<tr>
<td>DDH</td>
<td>1,618</td>
<td>1,584</td>
</tr>
<tr>
<td>M.DDH</td>
<td>9.63</td>
<td>9.43</td>
</tr>
</tbody>
</table>

N.DDH: Number of discomfort hours during the design weeks (summer and winter); DDH: discomfort degree hours; M.DDH: Mean discomfort degree hours.

The discomfort degree hours indicated that the 200.normal and Waffle.normal construction types would have a lower overheating peak (i.e. lower DDH in Table 6-10) during the summer design week.
10) in summer and winter conditions than the 200.low and Waffle.low types across the five major cities studied. A good example of the different discomfort degrees hours (DDH) between the four construction types is given in Figure 6-17 for climates 1 and 6. Note that the effects of structural materials (types of concrete) and construction forms (Flat and Waffle slabs) on indoor thermal conditions are slightly more noticeable in cold and moderate climates than hot and warm climates. The results of the other four climate zones are provided in Appendix E.

Figure 6-17 Discomfort degree hours during summer design week for climate zones 1 (Darwin) and 6 (Melbourne)

Figures 6-8 to 6-17 show that the thermal properties of structural concrete have more influence on the thermal performance of a building than the weight of the structure; in
fact the thermal properties of concrete (i.e. Ultra-lightweight versus Normal weight concrete) have a greater effect on the indoor air temperatures as the outside air temperature increases, and the differences between indoor air temperatures due to different structures (i.e. Flat slab versus Waffle slab) are more visible in moderate and cold climates.

6.5 Conclusion

This Chapter aimed to evaluate the impact that alternative concrete floor designs have on the energy performance of a typical office building. This Chapter used a benchmarking method to measure the thermal energy performance of a building using two forms of construction (Flat slab and Waffle slab) and two types of concrete (conventional Normal weight and novel Ultra-lightweight). The structural design analysis provided the maximum and minimum building mass for the Flat slab and Waffle slab respectively, which were then used to simulate the energy performance for whole buildings.

This Chapter analysis revealed how well structures with a higher thermal mass could moderate fluctuations between inside and outside air temperatures; those buildings with a higher concrete mass (thermal mass) stored more heat which then reduced the peak indoor air temperatures. Moreover, when Flat and Waffle slab structures are constructed from Normal weight concrete they have a similar energy performance, whereas Ultra-lightweight concrete resulted in indoor temperatures that are more sensitive to fluctuations in external air temperatures, so the building requires more energy to achieve the desired indoor temperature range.

This comparative analysis also revealed that choosing the appropriate type of concrete and construction form could reduce the annual cooling energy demand by a highly-
glazed office building by 14% in the colder climate zones and by 3% in warmer and hot climates.

The hourly free-floating simulation showed that a building with Ultra-lightweight concrete would experience higher daily peak indoor air temperatures during daytime, while the Lightweight building with Novel Ultra-lightweight experienced large increases of peak indoor air temperatures during the design weeks (Summer and Winter) by 1.2°C to 2.4°C in the hot and cold climate zones, respectively; in fact this type of highly glazed office building risked overheating during the summer and winter periods.

These indoor thermal conditions confirm that buildings where conventional Normal weight concrete is used for the structural elements (slabs, columns and shear walls) had less discomfort degree hours during the design weeks than the novel Ultra-lightweight concrete.

Finally, an appropriate structural design in which the energy performance is also considered could lead to reductions in the thermal energy demand for office buildings. Moreover, the magnitude of the impact of a structural system on the thermal performance of a structure could be changed across different alternatives. This Chapter highlights how important it is to look beyond the designed structural system and evaluate its impact with a holistic analysis. The whole life cycle environmental impact and costs associated with structural design alternatives are addressed in Chapter 7.
Chapter 7

Integrated life cycle cost method for low CO₂-e emissions structural design by focusing on a benchmark office building in Australia

Contribution of the candidate to the Published Work

The contribution of the candidate in the published paper was 90%. He co-authored them with his main and co-supervisors. The candidate modelled, simulated a case study building for energy analysis and wrote the paper. Other authors reviewed the papers and provided useful feedback for improvement.

Citation: Accepted (Manuscript number: ENB_2017_2644)

7.1 Introduction
Chapter 6 investigated the possible effects that conventional and novel concrete materials would have on the thermal performance of typical office buildings in Australia. The combination of lifetime CO₂-e emissions impacts and energy performance in economic terms provides a framework to compare and evaluate the sustainability of the construction solutions because cost is a key factor that must be considered in the decision making process. The recent awareness of environmental problems has highlighted the need to include possible environmental impacts and building costs into the decision making process, but thus far this combination has received scant attention. This Chapter therefore proposes to integrate the CO₂-e emissions and building costs into the structural design process using a method which includes the costs associated with building materials, construction methods and the amount of embodied carbon emissions during the life cycle of buildings. This Chapter analyses the effects that two construction systems (Flat slab and Waffle slab) and two structural materials (normal concrete and ultra-lightweight concrete) have on the overall costs of a typical high rise concrete structure (15-story office building) in Australia (NS11401.1 2014).

7.2 CO₂-e emissions impacts and life cycle cost analysis
The construction and building industry is responsible for a large part of the environmental burden because the Australian building sector, for example, uses almost 20% of Australia’s annual energy consumption and produces 23% of the GHG emissions (ABCB 2016). This situation will become even more critical due to the increasing number of houses (more than 3.3 million) resulting from the fast growth of population (NHSC 2011). A reduction in GHG is a vital need for Australia because
the nation committed to cope with carbon mitigation by 26-28% below the 2005 level by 2030 during the Paris UN Climate Conference (DEE 2015).

These growing pressures for CO$_2$-e emissions accountability have led to greater efforts to improve the sustainability of the building industry in Australia (Akbarnezhad et al. 2014; Crawford 2011; Ding & Forsythe 2013; Miller et al. 2013; Moussavi Nadoushani & Akbarnezhad 2015; Robati et al. 2016). Moreover, the need to assess the energy performance of buildings has extended from simply calculating the energy consumption during the operational phase to assessing sustainability over whole life cycle of buildings (Tian 2013; Tian & de Wilde 2011; Zuo et al. 2017).

Sustainability is now categorised into the environmental, social and economic aspects, so now most studies focus on the environmental and economic aspects of buildings by utilising Life Cycle Environmental Assessment (LCEA) and Life Cycle Cost Assessment (LCCA) (Cabeza et al. 2014; Ding 2014; Shahrestani et al. 2013; Sharma et al. 2011; Silva & Ghisi 2014; Singh et al. 2011; Zuo et al. 2017).

Some studies tried to optimise the structural design of buildings by considering its economic and environmental aspects; they have proposed a conceptual framework (called “Eco-efficiency method”) to measure sustainability by selecting the optimal product design and simultaneously considering the environmental impact and costs of the products (Cha et al. 2008; Hahn et al. 2010; Ji et al. 2014; Saling et al. 2002). Others propose to evaluate the environmental and economic impacts by converting embodied CO$_2$-e emissions into a momentary term over various stages of the building life cycle (Chou & Yeh 2015; Gu et al. 2008; Hong et al. 2013; Itsubo & Inaba 2003; Ji et al. 2014; Kim, J et al. 2012; Silvestre et al. 2014). Hong et al. (2012) proposed to integrate the cost and CO$_2$-e emissions associated with building structural design.
(using different grades of concrete 21-30 MPa), while Chou and Yeh (2015) studied the environmental impacts associated with the life cycle impacts of two construction methods (prefabrication and cast in place) by focusing on the consumption of fuel, electricity, and water.

Several researches quantified the effect that the structural materials have on the whole life energy performance of buildings (Anderson & Silman 2009; Appleby 2012; DIIS 2013; Lemay & Leed 2011; Torgal & Jalali 2011); their studies have shown that basic design decisions about structural elements (type of floor, shape of core servers, arrangements of columns, and heights of beams) have a direct impact on the energy consumption of buildings. For example, Aye et al. (2012) studied the life cycle energy usage for three forms of building construction in Melbourne, Australia; they considered an eight-story multi-residential building with three different construction systems: modular prefabricated timber, conventional concrete construction, and modular prefabricated steel (Aye et al. 2012) and showed that a steel structure caused a 50% increase in embodied energy compared to a concrete structure, but the steel structure reduced material consumption up to 78% by mass compared to the concrete structure.

Hajdukiewicz et al. (2015) studied the structural and environmental performance of operating a building; they used a monitoring method for educational buildings that were mainly built with in situ and precast concrete, and showed there was a distinct lag between the outdoor and indoor air temperature in the monitored elements. They also pointed out the positive role that Ground Granulated Blast furnace Slag (GGBS) had in reducing the internal peak temperatures, and concluded by showing that the
thermal mass used in the floor systems slowed the flow of heat through the elements and caused a temperature lag in the system.

Previous studies have highlighted the relative impact that decision making has on energy consumption, environmental performance, and life cycle cost of buildings, but there is still no study which uses all these aspects to determine the impact of structural design on energy performance, life cycle CO$_2$-e emissions, and life cycle costs in an integrated context for commercial buildings. Therefore, this Chapter proposes to integrate the CO$_2$-e emissions of a building structure over its lifetime as an environmental cost in order to provide a quantitative value for evaluating global CO$_2$-e emissions impacts made by different building structures in five Australian climate zones.

This Chapter is divided into different parts. The first part is the methodology which describes the method used to assess the integrated life cycle and analyse the whole of life costs associated with the research parameters. Section 7.3 describes the calculations of CO$_2$-e emissions associated with the building structure, energy modelling, and life cycle cost analysis. The results and discussion about the key findings associated with the research parameters are summarised in section 7.4.

7.3 Methodology

Commercial and office buildings are built to last for several decades, but over such a long period of time a building utilises a wide range of resources and energy intensive processes. Cost effectiveness is a key component of structural design at the initial stage of projects, so this Chapter analyses the life cycle cost and CO$_2$-e emissions impacts associated with a typical benchmark office building in Australia. This benchmark
building is one of four benchmarking buildings proposed by the National standard Organization (NSDO) in Australia (NS11401.1 2014). Figure 7-1 summarises all costs associated with a product or project over its lifetime, including the concept and definition, design and development, manufacturing and installation, operation and maintenance, and the disposal costs (AS/NZ4536 2014). This Chapter quantifies the life cycle costs associated with the office building by considering alternative structural materials and forms of construction; the life cycle costs include the initial costs, and the operational and maintenance costs (as shown in Equation 7-1).

\[ LCC = PV_{CP,C} + PV_{OP,C} + PV_{Rep,C} \]  

(7-1)

LCC = Life Cycle Cost

PV_{CP,C} = Present value of capital costs (initial costs)

PV_{OP,C} = Present value of operational costs (over 50 year lifetime)

PV_{Rep,C} = Present value of replacement costs (over 50 year lifetime)

Figure 7-1 Life cycle cost of building

The initial cost includes materials and construction expenses; the operation and maintenance costs consist of utilities costs and repair costs that occur only every several years over a 50-year service life. The costs associated with a feasibility study
(concept and definition), and the design, development, and discarding (disposal) are excluded from the scope of this Chapter.

The CO\textsubscript{2}-e emissions impact associated with the benchmark building was derived in terms of CO\textsubscript{2}-e emissions because they contribute to more climate change than other GHGs (methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride) (IPCC 2014; UNFCCC 2008). The environmental cost represents the cost of CO\textsubscript{2}-e emissions per tonne derived from the lifetime carbon emissions of buildings. Equation 7-2 is a method for estimating the costs associated with CO\textsubscript{2}-e emissions at each stage of a building’s life.

\[
EIM_{CO2-e} = PV_{IC.CO2} + PV_{OPC.CO2} \quad (7-2)
\]

\(EIM_{CO2-e}\) emissions = Environmental impact (CO\textsubscript{2}-e emissions) costs

\(PV_{IC.CO2-e}\) emissions = Present value of embodied CO\textsubscript{2}-e emissions cost

\(PV_{OPC.CO2-e}\) emissions = Present value of operational CO\textsubscript{2}-e emissions costs (over 50 year lifetime)

This comparison framework is used to integrate the life cycle costs and CO\textsubscript{2}-e emissions impact of several structural design alternatives and then choose the best alternatives. The environmental impact costs are estimated from the total GHGs emitted over the building’s lifetime and the present carbon value (as shown in Figure 7-2). In this Chapter the total GHGs emitted by the building consist of the state of the product, the construction stage, and use stage.
Figure 7-2 Environmental cost analysis method

Figure 7-3 shows how the global assessment framework provides a method to combine the life cycle and environmental impact costs over the lifetime of the building. The economic value includes the life cycle cost (initial costs, and operational and maintenance costs) and environmental costs which includes the total equivalent CO$_2$-e emissions cost, as a method to choose the most suitable structural design. This method compares the global costs across alternative building designs and delivers an outcome of cost results as a single global assessment parameter. This comparison framework integrates the results of life cycle costs and the environmental impacts of several structural design alternatives to help select the best alternatives.
7.3.1 Initial cost assessment method

The initial cost of the building includes the materials, transportation, and construction process. The quantities of building materials are from NS11401.1 (2014), the quantity of concrete and steel reinforcement comes from the detailed structural design (shown in Appendix B), and the input data to estimate these costs comes from the commonly used Australian construction cost guides and published literature (Cordell 2016; Rawlinsons 2016). The base year taken was 2016, and the input climate data were classified based on five different climate zones across Australia: Darwin (climate zone 1); Brisbane (climate zone 2); Sydney (climate zone 5); Melbourne (climate zone 6); Canberra (climate zone 7) (NS11401.1 2014). The cost of Ultra-lightweight concrete was calculated based on its unique mix design (proposed as mixes 32 and 36 in (Robati et al. 2016)), and the relative cost was collected from supplier price lists such as Eastchem (2017) (supplier of hollow fly ash cenosphere) and Boral (2017) (supplier of other components). A summary of the building materials and associated costs and quantities are provided in Table 7-1. The quantities of materials used in the building (items 8 to 16) are derived from NS 11401.1 (NS11401.1 2014), and the estimated
quantities of structural materials (concrete and steel reinforcement) for the Flat slab and Waffle slab are based on a detailed structural analysis.

### Table 7-1 Summary of building materials and unit costs

<table>
<thead>
<tr>
<th>Building materials</th>
<th>Materials quantities</th>
<th>Materials base cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unit</td>
<td>Construction forms</td>
</tr>
<tr>
<td></td>
<td></td>
<td>F.S</td>
</tr>
<tr>
<td>Concrete on Ground (N20)</td>
<td>m³</td>
<td>250</td>
</tr>
<tr>
<td>Suspended concrete (N32)*</td>
<td>m³</td>
<td>2.77 5</td>
</tr>
<tr>
<td>Suspended concrete (N40)*</td>
<td>m³</td>
<td>124</td>
</tr>
<tr>
<td>Steel in concrete</td>
<td>tonne</td>
<td>411</td>
</tr>
<tr>
<td>Timber formwork</td>
<td>m²</td>
<td>36,250</td>
</tr>
<tr>
<td>Steel formwork</td>
<td>m²</td>
<td>11.16</td>
</tr>
<tr>
<td>Plastic based formwork</td>
<td>Number</td>
<td>218</td>
</tr>
<tr>
<td>Timber battens</td>
<td>m²</td>
<td>20.1</td>
</tr>
<tr>
<td>Steel eaves gutter</td>
<td>m²</td>
<td>0.21</td>
</tr>
<tr>
<td>Steel ridge flashing</td>
<td>m²</td>
<td>0.1</td>
</tr>
<tr>
<td>Steel fascia</td>
<td>m²</td>
<td>0.64</td>
</tr>
<tr>
<td>Steel downpipe</td>
<td>m²</td>
<td>2.25</td>
</tr>
<tr>
<td>Plasterboard</td>
<td>m²</td>
<td>205.92</td>
</tr>
<tr>
<td>Roof and ceiling insulation</td>
<td>m²</td>
<td>1.41</td>
</tr>
<tr>
<td>Wall insulation</td>
<td>m²</td>
<td>3.57</td>
</tr>
<tr>
<td>Steel doors and mechanisms</td>
<td>m²</td>
<td>20</td>
</tr>
<tr>
<td>Glass window</td>
<td>m²</td>
<td>------</td>
</tr>
</tbody>
</table>
7.3.2 Operation and maintenance costs assessment method

The operating costs of the building is based on the energy consumed over a 50-year service life, while the operating energy over the life cycle of buildings is calculated based on the simulated annual heating and cooling load. The estimated annual energy used was multiplied by the relative energy market forecasts up to 2040 (Economics 2015; Jacobs 2016) and the future method of calculation to extend the estimated costs of energy from 2040 to 2066 (a 50 year lifetime). Equation 7-3 was used to determine the present operational costs over a 50 year, although the future costs were then discounted by 7% as a nominal per year (Lawania & Biswas 2016).

\[
P_{V_{OP\cdot cost}} = \sum_{y=1}^{50} \frac{FEC}{(1+d)^n}
\]

\(P_{V_{OP\cdot cost}}\) = Present value of operational costs

\(FEC\) = future energy costs (based on the market forecast and future costs analysis)

\(d\) = discounted rate per year

\(n\) = the appropriate number of years

The present value associated with maintenance (replacement) costs is estimated for glass windows (25 years) and plasterboard (35 years), both of which have a shorter lifetime than the building (50 years) (Rauf & Crawford 2012). The costs of ongoing repair, replacement, refurbishment, and external site development are excluded from this Chapter.
7.3.3 Environmental costs estimation method

The most common category for environmental impact used in life cycle assessment is global warming, so this Chapter used CO$_2$-e emissions as a key method for assessing the environmental impact of various structural design alternatives. Here, the calculated CO$_2$-e emissions at each stage of the designed buildings (production, construction, end of life demolition and use) were included. For the production and construction phases, the CO$_2$-e emissions emitted while manufacturing and transporting the construction materials were estimated. The embodied CO$_2$-e emissions associated with construction work, transportation, and final demolition at the end of life is estimated at a level of about 1% (Ruuska & Häkkinen 2015; Sartori & Hestnes 2007).

During the operational stage, energy conversion results in the release of greenhouse gas emissions which was estimated by using the national emissions factor proposed by the Australian National Greenhouse Accounts (DEE 2016). The emissions factor used to convert the consumption of operational energy into CO$_2$-e emissions is a function of the electricity purchased and consumed in 2015 (Lawania & Biswas 2016). Electricity is a dominant energy source in the benchmark building to provide the required cooling load; Other energy sources do not contribute to total energy used (Robati et al. 2017). It must be considered that the emissions projections are inherently uncertain, and this uncertainty increases into the projected future emissions. Based on Australia’s report into emissions projections (DEE 2016), future emissions from the combustion of fuels to generate electricity are predicted at level of 186 Mt CO$_2$-e emissions in 2030, which is roughly equivalent to 2015 levels. As such, this Chapter uses a base year of 2015 to estimate the CO$_2$-e emissions associated with the energy usage stage of a building.
The values related to the embodied CO$_2$-e emissions of materials is extracted from the accessible literature (Alcorn 2003; AusLCI 2016; Crawford 2011; eTool 2014; Hammond et al. 2011; Moussavi Nadoushani & Akbarnezhad 2015; Robati et al. 2016). The mean distance from manufacturing companies to the site (the central business district for each city) is measured using the Google map tools (Poinssot et al. 2014). In the last stage, the environmental impact is converted into costs. The price of CO$_2$-e emissions is based on the Adams et al. (2014) method and the Australia Emissions Trading Scheme (Combet 2012) with an inflation rate of 3% per year (RBA 2016). Future CO$_2$-e emissions is discounted at 7% as a nominal rate per year (Lawania & Biswas 2016). Equation 7-4 provides a present value for the costs of CO$_2$-e emissions over the lifetime of the buildings.

$$PV_{CO_2-e\,\,cost} = \sum_{y=1}^{50} \frac{CP_{CO_2-e\,\,emissions} \times (1+a)^n}{(1+d)^n}$$  

(7-4)

$PV_{CO_2-e\,\,emissions} = \text{Present value of CO}_2\text{-e emissions costs}$

$CP_{CO_2-e\,\,emissions} = \text{Current CO}_2\text{-e emissions price}$

$a = \text{is the expected increase in price per year (inflation rate)}$

$d = \text{discounted rate per year}$

$n = \text{the appropriate number of years}$

### 7.3.4 Building design and construction

The system for constructing the proposed 15 story office building is a mid-rise concrete structure (NS11401.1 2014); it has a square plan shape with a gross area of 1000 m$^2$, and consists of twelve 3.30 metre high stories and three floors of parking (as
shown in Figure 7-4). The geometry and construction materials are summarised in Table 7-2.

Table 7-2 Overall specification for the benchmark building

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basement dimensions</td>
<td>m</td>
<td>31.62 × 31.62</td>
</tr>
<tr>
<td>Number of Stories</td>
<td>---</td>
<td>15</td>
</tr>
<tr>
<td>Concrete slab on ground</td>
<td>mm</td>
<td>200</td>
</tr>
<tr>
<td>Concrete suspended slab</td>
<td>mm</td>
<td>175</td>
</tr>
<tr>
<td>Average elevation per floor</td>
<td>m</td>
<td>3.3</td>
</tr>
<tr>
<td>Total floor Area (including parking, Stairs &amp; Verandas)</td>
<td>m2</td>
<td>15,000</td>
</tr>
<tr>
<td>Total habitable area (external dimensions)</td>
<td>m2</td>
<td>8,807.1</td>
</tr>
<tr>
<td>Number of floors above ground level</td>
<td>---</td>
<td>11</td>
</tr>
<tr>
<td>Number of rooms</td>
<td>---</td>
<td>176</td>
</tr>
</tbody>
</table>

Figure 7-4 Template of 15-storey commercial office building as visualised in DesignBuilder
The structural system is designed to meet the minimum needed to satisfy the national construction code (ABCB 2015; AS3600 2009; AS/NZ1170.0 2002) (as shown in Table 7-3).

Table 7-3 Summary of the structural design

<table>
<thead>
<tr>
<th>Construction form</th>
<th>Flat slab (F.S)</th>
<th>Waffle slab (W.S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Column span distance (L)</td>
<td>5.27 m</td>
<td>5.27 m</td>
</tr>
<tr>
<td>Slab thickness (D)</td>
<td>200 mm</td>
<td>250 mm</td>
</tr>
<tr>
<td>Concrete quantities</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N20</td>
<td>250</td>
<td>250</td>
</tr>
<tr>
<td>N32</td>
<td>3,005</td>
<td>2,002</td>
</tr>
<tr>
<td>N40</td>
<td>124</td>
<td>124</td>
</tr>
<tr>
<td>Steel quantities (Tonne)</td>
<td>753</td>
<td>679</td>
</tr>
</tbody>
</table>

This current Chapter evaluated the possible effects of normal and low-density concrete with a higher weight (Flat slab) and lower weight (Waffle slab) office structure when the most common (Normal Weight) and novel (ultra-lightweight) concrete materials are used. The types of concrete mix designs were extracted from previously published journal papers and databases (CCAA 2015; O’Moore & O’Brien 2009; Robati et al. 2016; Wu et al. 2015; Yun et al. 2013) (shown in Table 7-3).

7.3.5 Energy modelling

To analyse the energy over the lifetime of the project, this office building is modelled in DesignBuilder (energy simulation software) so that the effects of alternative structural systems on the energy consumption could be assessed. This Chapter used the Building Code of Australia (BCA) “deemed to satisfy” approach to define the
envelope construction of this building (as shown in Table 7-3). The concrete thermal resistance and thermal mass, as two of the more prominent aspects of an energy analysis of building, are presented in Table 7-4 below.

**Table 7-4 Benchmark building physical properties**

<table>
<thead>
<tr>
<th>Elements</th>
<th>R-values (m$^2$.K/W)</th>
<th>Item description</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground floor</td>
<td>1.25</td>
<td>Solid concrete*1 (150 mm, 2400 kg/m$^3$)</td>
<td>(ABCB 2015)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Solid concrete (Study parameters)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>a. 1.250</td>
<td>a. Flat slab with Normal Weight concrete*1</td>
<td>(ABCB 2015)</td>
</tr>
<tr>
<td></td>
<td>b. 1.81</td>
<td>b. Flat slab with Ultra-lightweight concrete*2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>c. 1.216</td>
<td>c. Waffle slab with Normal Weight concrete*1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>d. 1.627</td>
<td>d. Waffle slab with Ultra-lightweight concrete*2</td>
<td></td>
</tr>
<tr>
<td>Slabs</td>
<td></td>
<td>Solid concrete, (Study parameters)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>a. 4.203</td>
<td>a. Flat slab with Normal Weight concrete*1</td>
<td>(ABCB 2015)</td>
</tr>
<tr>
<td></td>
<td>b. 4.836</td>
<td>b. Flat slab with Ultra-lightweight concrete*2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>c. 4.169</td>
<td>c. Waffle slab with Normal Weight concrete*1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>d. 4.581</td>
<td>d. Waffle slab with Ultra-lightweight concrete*2</td>
<td></td>
</tr>
<tr>
<td>Roof</td>
<td></td>
<td>2. 125 mm minimum solid reinforced concrete*1</td>
<td>(ABCB 2015)</td>
</tr>
<tr>
<td>Wall</td>
<td>3.42</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Window</td>
<td>U value was taken as 5.80 with SHG=0.81 for all climates</td>
<td></td>
<td>(Daly et al. 2014; Guan 2009)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Grade (MPa)</th>
<th>*1 Normal Weight concrete</th>
<th>*2Ultra-lightweight concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>40(a)</td>
<td>32(b)</td>
</tr>
<tr>
<td>Density (Kg/m$^3$)</td>
<td>2393</td>
<td>2470</td>
</tr>
<tr>
<td>Thermal conductivity(W/mK)</td>
<td>1.96</td>
<td>2.10</td>
</tr>
<tr>
<td>Specific heat (kJ/(kg.k))</td>
<td>0.88</td>
<td>0.88</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Grade (MPa)</th>
<th>40(a)</th>
<th>32(b)</th>
<th>20(c)</th>
<th>40(a)</th>
<th>32(b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (Kg/m$^3$)</td>
<td>2393</td>
<td>2470</td>
<td>1744</td>
<td>1400</td>
<td>1164</td>
</tr>
<tr>
<td>Thermal conductivity(W/mK)</td>
<td>1.96</td>
<td>2.10</td>
<td>1.18</td>
<td>0.31</td>
<td>0.28</td>
</tr>
<tr>
<td>Specific heat (kJ/(kg.k))</td>
<td>0.88</td>
<td>0.88</td>
<td>0.88</td>
<td>0.88</td>
<td>0.88</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Grade (MPa)</th>
<th>40(a)</th>
<th>32(b)</th>
<th>20(c)</th>
<th>40(a)</th>
<th>32(b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (Kg/m$^3$)</td>
<td>2393</td>
<td>2470</td>
<td>1744</td>
<td>1400</td>
<td>1164</td>
</tr>
<tr>
<td>Thermal conductivity(W/mK)</td>
<td>1.96</td>
<td>2.10</td>
<td>1.18</td>
<td>0.31</td>
<td>0.28</td>
</tr>
<tr>
<td>Specific heat (kJ/(kg.k))</td>
<td>0.88</td>
<td>0.88</td>
<td>0.88</td>
<td>0.88</td>
<td>0.88</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Grade (MPa)</th>
<th>40(a)</th>
<th>32(b)</th>
<th>20(c)</th>
<th>40(a)</th>
<th>32(b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (Kg/m$^3$)</td>
<td>2393</td>
<td>2470</td>
<td>1744</td>
<td>1400</td>
<td>1164</td>
</tr>
<tr>
<td>Thermal conductivity(W/mK)</td>
<td>1.96</td>
<td>2.10</td>
<td>1.18</td>
<td>0.31</td>
<td>0.28</td>
</tr>
<tr>
<td>Specific heat (kJ/(kg.k))</td>
<td>0.88</td>
<td>0.88</td>
<td>0.88</td>
<td>0.88</td>
<td>0.88</td>
</tr>
</tbody>
</table>

a. Grade N40 used in the vertical structural elements such as columns and shear walls.
b. Grade N32 used in the slabs (Waffle and Flat).
c. Grade N23 used in the other concrete element (staircase).
The internal energy loads in the office building form a large portion of energy usage and are significant input parameters in the energy analysis. Table 7-5 summarises the assumptions made to analyse the energy of the benchmark building. The schedules associated with the building are extracted from ABCB (2015).

**Table 7-5 Benchmark building simulation assumptions**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Key variables</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lighting power density and schedule</td>
<td>9 (W/m²)</td>
<td>(ABCB 2015)</td>
</tr>
<tr>
<td>Occupancy density and schedule</td>
<td>10 (m²/person)</td>
<td>(ABCB 2015)</td>
</tr>
<tr>
<td>Equipment load and schedule</td>
<td>15 (W/m²)</td>
<td>(ABCB 2015)</td>
</tr>
<tr>
<td>Domestic hot water</td>
<td>0.4 (L/m²)</td>
<td>(ABCB 2015)</td>
</tr>
<tr>
<td>Infiltration</td>
<td>0.28 (ACH)</td>
<td>(Egan 2011)</td>
</tr>
<tr>
<td>Ventilation requirements and schedule</td>
<td>10 (L/s/person)</td>
<td>(ABCB 2015)</td>
</tr>
<tr>
<td>HVAC set point</td>
<td>18-26 °C</td>
<td>(ABCB 2015)</td>
</tr>
<tr>
<td>HVAC</td>
<td>DesignBuilder</td>
<td>(CCAA 2015; Robati et al. 2016)</td>
</tr>
<tr>
<td></td>
<td>Simple HVAC, Auto size</td>
<td></td>
</tr>
</tbody>
</table>

The results of modelling the benchmark building are shown in terms of total energy usage across different design alternatives. Here the total energy consumption is compared with national and states average energy usage to ensure that the predicted energy consumption is realistic (Pitt&Sherry 2012), and then, at the final stage, the total energy consumption of the benchmark building across four climates is converted into the equivalent energy costs and environmental costs (equivalent CO₂-e emissions).
7.4 Results and Discussion

7.4.1 Lifetime environmental impacts

Figure 7-5 is a comparison between whole of life CO₂-e emissions for the benchmark office building across five major climate zones. Note that the region dominated by heat such as Darwin has higher CO₂-e emissions than the colder climate zones (Canberra and Melbourne) due to the high cooling load during the operational phase of the building in the hot climate where total CO₂-e emissions are much higher than cold climates. Moreover, CO₂-e emissions associated with these buildings reveal that Ultra-lightweight concrete released more CO₂-e emissions than conventional concrete, and the heavier building with Ultra-lightweight concrete (200.low) produced highest carbon dioxide emissions (CO₂-e /m²) across all five major cities. The NABERS (National Australian Built Environment Rating System) rating tool revealed that the environmental impact of these different design alternatives scored from 1 star (poor performance) to 3.5 stars (above average performance). The buildings located in Darwin and Canberra had the lowest (1 star) and highest (3.5 star) environmental impact rating, respectively, but more importantly, these ratings changed across various design alternatives in some regions; in Melbourne for instance, the lighter weight building made from novel concrete had a lower rating (2.5 star) than the others, which means that the selection of structural materials and the form of construction influences the overall environmental ratings.
Waffle.low: Lightweight structure (Waffle slab) with Ultra-lightweight concrete; Waffle.normal: Lightweight structure (Waffle slab) with Normal Weight concrete; 200.low: heavyweight structure (200mm Flat slab) with Ultra-lightweight concrete; 200.Normal: heavyweight structure (200mm Flat slab) with Normal Weight concrete.

Figure 7-5 Annual GHG (CO₂-e emissions) normalised by net internal area (m²)

Figure 7-6 shows the CO₂-e emissions intensity associated with different phases of life cycle for two cities with the highest and lowest amount of CO₂-e /m². The first bar shows the CO₂-e emissions related to the production phase, the construction phase and the end of life (demolition) phase of the building; the second bar shows the CO₂-e emissions from operational phase of the building over a 50 year lifetime, and the last bar is the whole life CO₂-e emissions for each alternative design. These results reveal how the range of CO₂-e emissions for the buildings is influenced by changes in the type of concrete and type of construction. For instance, the Lightweight structures designed with Ultra-lightweight concrete had higher CO₂-e emissions (5% in Canberra and 2% in Darwin) than the other design alternatives, whereas the Lightweight structure made from Normal weight concrete (Waffle.Normal) has the lowest CO₂-e
emissions across both cities. This trend can be seen in the other three main cities (as shown in Appendix F).

*ACT average state CO₂-e emissions (kg/m²) intensity: 12,140 (BZE 2013; Pitt&Sherry 2012)

*NT average state CO₂-e emissions (kg/m²) intensity: 9,421 (BZE 2013; Pitt&Sherry 2012)

Waffle.low: Lightweight structure (Waffle slab) with Ultra-lightweight concrete; Waffle.normal: Lightweight structure (Waffle slab) with Normal Weight concrete; 200.low: heavyweight structure (200mm Flat slab) with Ultra-lightweight concrete; 200.normal: heavyweight structure (200mm Flat slab) with Normal Weight concrete.

**Figure 7-6** Life cycle CO₂-e emissions normalised by the gross floor area and separated by the type of concrete and method of construction.

### 7.4.2 Present value environmental costs of buildings

The environmental life cycle cost includes the total cost associated with CO₂-e emissions over the whole life (50 years) of the office buildings. This Chapter estimated the CO₂-e emissions at the production (peruse), construction, use stage, and end of life demolition. The CO₂-e emissions of the final phase was considered at a 1% level by previous studies (Ruuska & Häkkinen 2015; Sartori & Hestnes 2007). Figure 7-7 shows the present environmental life cycle cost for four design scenarios (different forms of construction and structural materials), and the present cost of CO₂-e emissions (Australian dollars) per m² net internal area.
Figure 7-7 Environmental costs of the buildings

Figure 7-7 shows that the Lightweight building (Waffle slab) constructed with Ultra-lightweight concrete has the highest amount of carbon emissions costs ($AUD) per normalised CO2-e emissions for the net settlement area (Tonne CO2-e /m²) over the lifetime of the buildings, while the Waffle slab with Normal weight concrete has the lowest carbon emissions costs. This shows that Ultra-lightweight concrete can cost up to 5% more over the whole of life environmental costs than Normal weight (conventional) concrete, which means the type of concrete used is a large part of the total CO2-e emissions. For Melbourne, the total carbon cost per m² (net internal area) of the building changed from 170 to 180 ($AUD/ (Tonne CO2-e /m²)) when Ultra-lightweight is used as the main structural material. This change in cost of CO2-e emissions also occurs when the heavier building consists of 200mm thick Flat slabs (200.normal and 200.low).
7.4.3 Life cycle cost analysis

7. Capital costs

This Chapter evaluated the capital costs associated with Flat slab and Waffle slab construction methods and Normal and Ultra-lightweight concrete across five regions (as shown in Figure 7-8).

![Figure 7-8 Initial capital costs (construction) of the building](image)

The results show that the average cost of a Lighter weight structure (Waffle Slab) with Normal Weight concrete is less than the heavier structure (Flat slab). For example, the initial cost of the building in Melbourne with Waffle slab and Normal Weight concrete is 6% lower than the Flat slab with normal concrete (200.normal), however, Ultra-lightweight concrete in the structure resulted in higher capital cost in all five climate zones. The initial cost of the building with a Flat slab with Ultra-lightweight concrete (200.low) is higher than the cost of the construction systems. As the literature highlights, the availability of supplementary cementitious materials used in Ultra-lightweight concrete is limited compared to Normal Weight concrete, so the costs are higher (Glavind 2012). For instance, the cost of Ultra-lightweight concrete used in this
Chapter is affected mainly by the price of Cenosphere (hollow particles from the production of fly ash) which is higher than the other concrete components (Eastchem 2017). Apart from the costs, there are still obstacles to the use of Lightweight and/or Ultra-lightweight concrete, i.e., regulatory, technical, and supply chain (Cabeza et al. 2013; Duxson & Provis 2008; Van Deventer et al. 2012). There are several research programs currently aiming to remove these obstacles to allow for a wider use of Lightweight and/or Ultra-lightweight concretes (Huiskes et al. 2016; Yu, R et al. 2015), so it is worth considering when Ultra-lightweight concrete may become more available.

8. Operating and maintenance costs of the buildings

The present values associated with the operating expenses are derived from forecasts of energy consumption and energy prices; these simulations were used to determine the operation costs over the lifetime of buildings (50 years). The maintenance costs are compared to the present value and the cost of replacing materials with shorter lifespans than buildings (50 years), such as glass windows (25 years) and plasterboard (35 years) (Rauf & Crawford 2012). Figure 7-9 shows the costs associated with Energy consumption and the materials used across five cities in Australia. The cost analysis shows that Darwin with its warm winter and hot summer had the highest energy consumption, while Melbourne, with its mild temperature had lower energy consumption than the other cities; however the operational costs are much higher than the replacement costs over the lifetime of the buildings. The energy performance was influenced by the methods of construction (Flat slab and Waffle slab) and the types of structural materials (concrete density: Normal Weight and Ultra-lightweight). The results show that selecting the right forms of construction and type of concrete could
save 2.4% of the running costs (during lifetime) for the building in Darwin and 5% for the other cities (Brisbane, Sydney, Melbourne, and Canberra). The Lightweight office building (Waffle) with Normal Weight concrete (Waffle.normal) has lower running costs than the alternatives, whereas the operating and replacement costs associated with the analysis reveal a consistently higher expenditure for the Waffle slab made from low density concrete (Ultra-lightweight).

![Graph: Present value of operating & maintenance costs (PV AUD $/m²)](image)

**Figure 7-9 Present value of operational and replacement costs of the building**

### 7.4.4 Combined life cycle environmental and cost net present value

Table 7-6 summarises the whole life cycle cost assessment of the office building across five major cities in Australia; these costs are presented as environmental costs and life cycle cost (a combination of capital cost, operating costs, and maintenance costs) per net internal area. These results indicate that the energy demand at the operational phase and capital phase are the highest proportion of costs over the 50 year lifetime of the building. The equivalent cost of CO₂-e emissions from production, construction, use, and demolition (end of life) can be up to 5% of the total cost of the buildings across all cities and design alternatives. The overall cost (LCCA+)
Environmental costs of the office building in Sydney ranged from to 4,017 ($AUD/m²) for the Waffle slab with normal concrete (Waffle.normal) to 4,189 ($AUD/m²) for the Flat slab with Ultra-lightweight concrete (200.low).

Table 7-6 Whole life environmental and life cycle cost assessment of the building

<table>
<thead>
<tr>
<th>Location</th>
<th>Type of Building</th>
<th>PV. Initial cost ($AUD/m²)</th>
<th>PV. Operational and replacement cost ($AUD/m²)</th>
<th>LCCA ($AUD/m²)</th>
<th>PV. Environmental cost ($AUD/m²)</th>
<th>Total costs ($AUD/m²)</th>
<th>Comparison (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melbourne</td>
<td>200.normal</td>
<td>1,819</td>
<td>1,611</td>
<td>3,431</td>
<td>172</td>
<td>3,603</td>
<td>+2%</td>
</tr>
<tr>
<td></td>
<td>200.low</td>
<td>1,870</td>
<td>1,642</td>
<td>3,512</td>
<td>176</td>
<td>3,688</td>
<td>+5%</td>
</tr>
<tr>
<td></td>
<td>Waffle.normal</td>
<td>1,743</td>
<td>1,612</td>
<td>3,354</td>
<td>170</td>
<td>3,525</td>
<td>----</td>
</tr>
<tr>
<td></td>
<td>Waffle.low</td>
<td>1,779</td>
<td>1,696</td>
<td>3,475</td>
<td>180</td>
<td>3,655</td>
<td>+4%</td>
</tr>
<tr>
<td>Canberra</td>
<td>200.normal</td>
<td>1,830</td>
<td>1,750</td>
<td>3,580</td>
<td>140</td>
<td>3,720</td>
<td>+2%</td>
</tr>
<tr>
<td></td>
<td>200.low</td>
<td>1,853</td>
<td>1,786</td>
<td>3,639</td>
<td>144</td>
<td>3,783</td>
<td>+4%</td>
</tr>
<tr>
<td></td>
<td>Waffle.normal</td>
<td>1,754</td>
<td>1,751</td>
<td>3,505</td>
<td>139</td>
<td>3,644</td>
<td>----</td>
</tr>
<tr>
<td></td>
<td>Waffle.low</td>
<td>1,770</td>
<td>1,840</td>
<td>3,610</td>
<td>146</td>
<td>3,756</td>
<td>+3%</td>
</tr>
<tr>
<td>Sydney</td>
<td>200.normal</td>
<td>1,836</td>
<td>2,096</td>
<td>3,932</td>
<td>167</td>
<td>4,099</td>
<td>+2%</td>
</tr>
<tr>
<td></td>
<td>200.low</td>
<td>1,868</td>
<td>2,149</td>
<td>4,017</td>
<td>171</td>
<td>4,189</td>
<td>+4%</td>
</tr>
<tr>
<td></td>
<td>Waffle.normal</td>
<td>1,755</td>
<td>2,096</td>
<td>3,852</td>
<td>165</td>
<td>4,017</td>
<td>----</td>
</tr>
<tr>
<td></td>
<td>Waffle.low</td>
<td>1,779</td>
<td>2,207</td>
<td>3,986</td>
<td>174</td>
<td>4,160</td>
<td>+4%</td>
</tr>
<tr>
<td>Brisbane</td>
<td>200.normal</td>
<td>1,817</td>
<td>2,678</td>
<td>4,495</td>
<td>199</td>
<td>4,694</td>
<td>+2%</td>
</tr>
<tr>
<td></td>
<td>200.low</td>
<td>1,870</td>
<td>2,744</td>
<td>4,614</td>
<td>204</td>
<td>4,818</td>
<td>+4%</td>
</tr>
<tr>
<td></td>
<td>Waffle.normal</td>
<td>1,741</td>
<td>2,681</td>
<td>4,423</td>
<td>198</td>
<td>4,620</td>
<td>----</td>
</tr>
<tr>
<td></td>
<td>Waffle.low</td>
<td>1,779</td>
<td>2,806</td>
<td>4,585</td>
<td>207</td>
<td>4,792</td>
<td>+4%</td>
</tr>
<tr>
<td>Darwin</td>
<td>200.normal</td>
<td>1,841</td>
<td>4,206</td>
<td>6,047</td>
<td>260</td>
<td>6,307</td>
<td>+1%</td>
</tr>
<tr>
<td></td>
<td>200.low</td>
<td>1,864</td>
<td>4,229</td>
<td>6,093</td>
<td>262</td>
<td>6,356</td>
<td>+2%</td>
</tr>
<tr>
<td></td>
<td>Waffle.normal</td>
<td>1,769</td>
<td>4,218</td>
<td>5,987</td>
<td>259</td>
<td>6,246</td>
<td>----</td>
</tr>
<tr>
<td></td>
<td>Waffle.low</td>
<td>1,786</td>
<td>4,311</td>
<td>6,096</td>
<td>265</td>
<td>6,362</td>
<td>+2%</td>
</tr>
</tbody>
</table>

PV: Present value
Waffle.low: Lightweight structure (Waffle slab) with Ultra-lightweight concrete; Waffle.normal: Lightweight structure (Waffle slab) with Normal Weight concrete; 200.low: heavyweight structure (200mm Flat slab) with Ultra-lightweight concrete; 200.Normal: heavyweight structure (200mm Flat slab) with Normal Weight concrete

This result indicates that a Waffle slab with an appropriate type of concrete (Normal Weight) can save up to $156 per m² (average value across all cities) in the total life
cycle cost of the building across all five major cities, whereas the use Ultra-light weight concrete in the Flat slab increased the total costs of the building by almost 3% compared to Normal weight (conventional) concrete. A comparison between the Waffle slab and Flat slab, including Normal weight concrete, reveals that a lightweight structure with Normal weight concrete (Waffle.normal) can consistently save up to 2% in the total cost of the building, whereas the total cost associated with buildings constructed from Ultra-lightweight concrete across a lightweight structure (Waffle.low) and heavyweight structure (200.low) has not changed, and moreover, of the methods of construction and structural materials are more tangible in colder climates than hotter climates such as Melbourne and Darwin.

7.5 Conclusion

This current Chapter assessed how different structural designs and construction systems affected the environmental impact and life cycle costs of a typical office building in Australia. The two main parameters in this Chapter are the method of construction (Flat slab and Waffle slab) and the type of concrete (Normal Weight and Ultra-lightweight) used as structural materials. This Chapter finds that the total life cycle cost of buildings is influenced by the selection of structural materials and system of construction, indeed it has been shown that an appropriate building design can save almost 7% of the cost of material consumption, 5% of the total energy consumption expense, and 5% of the CO2-e emissions. A Lightweight building with a Waffle slab and Normal density costs less than the other buildings (LCCA and environmental costs) across the five main climate zones; the heavyweight building with a Flat slab and Normal weight concrete is the second best design alternative, saving almost 3% in total costs compared to the other buildings.
The analysis of CO₂-e emissions costs shows that the use phase of the building is responsible for most CO₂-e emissions, while the other building phase accounts for almost 5% of total CO₂-e emissions. The present value of CO₂-e emissions varies from 6 to 9.5 $AUD/m² depending on the type of concrete, method of construction, and the climate of the city. The operational phase shows that CO₂-e emissions due to energy consumption is strongly influenced by the weight of construction and type of concrete (Normal Weight and Ultra-lightweight) used in the building. In general, a Lightweight building with normal density concrete uses less energy than the alternatives, and therefore produces less CO₂-e emissions during the operating phase.

The findings of this Chapter show that selecting the optimal structural design based on a single-phase life cycle assessment might make it difficult to choose the ideal design alternatives. This is why all the stages of life cycle assessment must be considered when selecting alternative designs to achieve more environmentally friendly buildings.

The findings of this Chapter might be used as a guideline to optimise the performance of concrete structures by considering the efficiency of the structural materials and construction systems, but further studies must consider the potential impact of other structural forms (timber, steel and Post-tensioned) on the whole life cycle of buildings. A summary of key findings and contribution of this research are provided in Chapter 8.
Chapter 8

Conclusion

8.1 Introduction

This Chapter draws together a series of publications leading to thesis by publication work. Chapters 4-7 have each been published or accepted for publication and combined give a coherent narrative of this research.

Chapter 4 incorporates embodied CO$_2$-e emissions and thermal properties associated with the selection of concrete mix designs. The inconsistency in results of embodied CO$_2$-e emissions (as shown in Section 4.6) lead Chapter 5 to take into the account the uncertainties associated with the lifetime embodied CO$_2$-e emissions of building materials and their impact on buildings. Chapter 5 takes into the account the uncertainties associated with the lifetime embodied CO$_2$-e emissions of building materials and their impact on four different structural systems.

The question about potential impact of novel construction materials (as shown in Section 4.7) is addressed in Chapter 6. The Chapter assesses the impact that structural design alternatives have on the energy demands and thermal performance of an office building in Australia.

Finally, Chapter 7 combines lifetime CO$_2$-e emissions impacts and energy performance in economic terms to compare and evaluate the effects that two construction systems (Flat slab and Waffle slab) and two structural materials (normal concrete and ultra-lightweight concrete) have on the overall costs and sustainability of a typical high rise concrete structure in Australia. Chapter 7 proposes a framework to
demonstrate how different structural alternatives affect the lifetime energy consumption, the materials used, the CO₂-e emissions, and the costs in a building.

The literature review and my publications that make up this thesis explore the life cycle CO₂-e emissions necessary for the structural engineering design of multi-storey office buildings. This research highlighted a specific gap in the existing knowledge in the structural design of buildings. A number of research studies have considered the environmental impact that structural design has on different phases of a building’s life cycle, but no detailed work, until now, that assessed the CO₂-e emissions and costs associated with selecting structural materials and forms over the lifetime of buildings. Hence, this thesis examines the impact that structural design alternatives have over the lifetime of a building by using existing measurement tools and simulation methods. This PhD identifies and quantifies the potential impact of structural design decisions and construction practices in an Australian context. The outcomes of this current PhD contribute to our knowledge by addressing the effects of structural design on lifetime costs, environmental impacts by focusing on CO₂-e emissions, energy usage, and thermal performances of a building in Australia.

8.2 Review of aims and objectives

The primary aim of this PhD was to explain the impact that structural design decisions have on the life cycle impacts of buildings by achieving the key objectives which is shown in section 1.5.

This research was carried out in a number of distinct steps to address the objectives presented in Chapter 1 (section 1.5). The methodology used in this research (see Chapter 3) was formed on the existing multi-assessment method to investigate the research questions from various perspectives. The key methodology consists of:
(1) Determining the embodied CO\textsubscript{2}-e emissions impacts associated with various concrete design mix alternatives based on the method used in sections 3.6, 3.7 and 4.5. This stage considered the strategy proposed in the reviewed literature (sections 1.2, 2.3-2.5) to quantify CO\textsubscript{2}-e emissions associated with various types of concrete mixes.

(2) Implementing an uncertainty analysis to quantify the variations associated with lifetime CO\textsubscript{2}-e emissions of the design alternatives (as discussed in sections 1.2, 2.1 and 3.8). This stage of the study examines the uncertainties caused by selecting various types of building materials in four different construction systems (As shown in sections 3.8 and 5.4).

(3) Utilising an energy analysis method (sections 3.7 and 6.3.4) to identify the potential impact of selecting a conventional and novel type of concrete (as shown in section 2.9 and 6.1) on energy usage and thermal performance of the benchmark office building (as shown in 6.3.1), while considering the two commonly used constructional systems including: Flat slab and Waffle slab (as discussed in sections 2.12, 3.4, 6.3.2 and 6.3.3).

(4) Developing a framework to describe a lifetime of CO\textsubscript{2}-e emissions and construction costs (as discussed in sections 1.2.3, 2.8, 2.9) associated with various design alternatives at the initial stage of the decision making process (as shown in Chapter 7). This stage of the study used a method (sections 3.10 and 7.3) to include the costs associated with building materials, construction methods and the amount of embodied carbon dioxide emissions during the life cycle of buildings. This was conducted by considering variations and focusing on various types of structural concrete (conventional and novel...
concrete) that were used in two different construction systems (Waffle slab and Flat slab).

An overview of the key research findings is presented in the following section.

8.3 Research Findings Pertinent to the Research Objectives

1. Review existing literature in sustainability and sustainable building design and then identify the main key strategies, parameters, and tools associated with structural design;

The review of existing literature pertaining to sustainability and sustainable building design identified the key factors associated with the sustainable design of the building (Sections 2.2 to 2.5). The results indicate that the main strategies (as shown in Section 2.3) and parameters (a shown in Section 2.4) could have a considerable effect on the life cycle impact of buildings. Several multi-criterion rating and benchmarking systems, as well as tools and databases, describe the environmental impact associated with the production and consumption of different types of building materials (section 2.6). Much of the published work is based on limited system boundaries e.g. cradle to gate, or is focussed on the impact of material production only or on one stage of the life cycle. They do not consider the whole of life impacts (sections 2.8 and 2.9).

From the perspective of sustainable structural design, researchers have attempted to address the impact of structural systems on the environment by analysing a specific stage of a building’s life cycle (pre-use, use, or end of life) (section 2.8) (Asdrubali et al. 2013; Dixit et al. 2012; Ruuska & Häkkinen 2015; Saghafi & Teshnizi 2011; Torgal & Jalali 2011); only limited attention has been given to the comprehensive life cycle analyses (Cradle to Grave) needed to determine the impact of structural design during the lifetime performance of buildings. This literature review has indicated there is still a lack of information quantifying the CO2-e emissions impact that the form of
construction and the properties of structural materials has over a building’s lifespan. As such, a research methodology (Chapter 3) was developed to investigate the potential impact that structural solutions would have on the environmental and economic aspects of the lifetime impact of a building structure at the initial stage of decision making.

2. Investigate the relative impact that properties of selected construction materials will have on the environment at the initial stage of structural design;

The appropriate selection of structural materials has a significant impact on the environment. The results of Chapter 4 reveals that the environmental impact, as measured by embodied CO₂-e emissions, associated with various concrete mix designs as a structural material is systematically influenced by the cementitious materials used in Section 4.6.1. The analysis of thermal conductivity associated with concrete mix designs showed a direct relationship with the increasing density of concrete that is consistent with the relevant literature, as shown in section 4.6.3. Moreover, Section 4.6.3 also shows that lower density concrete mixes could have a higher CO₂-e emissions while providing a low thermal conductivity. This could be useful for energy saving during the operational stage of buildings but detrimental to the carbon footprint of construction.

Key findings:

- The embodied CO₂-e emissions associated with common structural grades of concrete (38-42 MPa) ranges from 211 to 509 kg CO₂-e /m³. This is directly related to the proportion of cement used in the mix design (section 4.6.1). The addition of readily available supplementary cementitious material can reduce
embodied CO₂-e emissions (kg CO₂-e emissions) by up to 16% compared to general practice.

- The embodied CO₂-e emissions for a selected grade of concrete (32MPa) can vary from 63 kg to 496 kg CO₂-e /m³ of concrete, but this depends on the type of mix design and inventory database (4.6.2). The comparison shows some inconsistencies in the calculation of embodied CO₂-e emissions across the different databases that are attributed to variations in the embodied CO₂-e emissions coefficients.

- Some of the embodied emissions databases currently available treated concrete as only one specific product, and thus proposed an individual embodied CO₂-e emissions factor for each grade of concrete, regardless of the mix of ingredients. This is an over simplification that leads to variations in estimating the environmental impact at the initial stage of life cycle analysis of buildings. Section 4.6.2 highlighted the need for transparency across the existing and future databases. A summary of these findings will determine the variations which could be used for comparison purposes for studies that used these databases.

3. **Investigate the uncertainty involved in the environmental impact that each construction material has on a typical high-rise office building;**

The results of section 4.6.2 show there are many variations in the selection of structural materials. The variations associated with a life cycle assessment of the structural solutions for a benchmark office building were considered in Chapter 5. The uncertainty analysis (section 5.5) revealed a specific range for the probability and reliability of the input parameters. The cumulative probability distribution curve revealed a range of embodied CO₂-e emissions for each construction material during
the lifetime of buildings from extraction of materials to the end of life demolition (section 5.4). The range of embodied CO$_2$-e emissions for each construction material shows the uncertainties associated with variations in input parameters and their influence on the overall life cycle environmental impact of buildings.

The results of Chapter 5 established a baseline for the proposed office building that can be used for the designing alternatives at the early stage of decision making to predict the embodied CO$_2$-e emissions impact over its whole life. Chapter 5 also provides a tool for assessing the long term impact of these early design decisions.

**Key findings:**

- The Waffle slab and Post-tensioned slab have the lowest total mean embodied CO$_2$-e emissions values compared to the Flat plate and Flat slab for the benchmark building (Table 8-1).

### Table 8-8-1 Embodied CO$_2$-e emissions associated with different structural forms

<table>
<thead>
<tr>
<th>Value</th>
<th>Type of structural system</th>
<th>F.S.R</th>
<th>F.P</th>
<th>P.T</th>
<th>W.S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min</td>
<td></td>
<td>145</td>
<td>127</td>
<td>102</td>
<td>119</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>359</td>
<td>354</td>
<td>298</td>
<td>292</td>
</tr>
<tr>
<td>Max</td>
<td></td>
<td>732</td>
<td>764</td>
<td>646</td>
<td>590</td>
</tr>
<tr>
<td>Standard deviation</td>
<td></td>
<td>83</td>
<td>94</td>
<td>81</td>
<td>71</td>
</tr>
</tbody>
</table>

F.S.R: Flat slab for the reference building in proposed span distance of 5.27 m and slab thickness of 185 mm (NS11401.1 2014); F.P: Flat plate in the reference building with span distance of 5.27 m and slab thickness of 200 mm; P.T: Post-tensioned slab in the reference building with span distance of 5.27 m and slab thickness of 175 mm; W.S: Waffle slab in the reference building with span distance of 5.27 m and slab thickness of 250 mm (50mm topping + 200 stem depth).
- The level of uncertainty associated with different types of concrete (N40, N32 and N20) ranged from 6% to 78% of the total embodied CO$_2$-e emissions of the building. This level of variation, as highlighted in the previous Chapter (section 4.6.2), comes from the significant difference in embodied CO$_2$-e emissions coefficients for each different concrete mix design. From the structural design perspective, selecting an appropriate type of concrete could substantially reduce the negative environmental impact of concrete.

- The structural materials (Concrete and steel reinforcement) and architectural elements (windows with aluminium frame) accounted for the highest proportions of embodied CO$_2$-e emissions (as shown in Table 6-2).

**Table 8-2 Variations in embodied CO$_2$-e emissions of the materials used in the buildings**

<table>
<thead>
<tr>
<th>Materials</th>
<th>Min</th>
<th>Mean</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Suspended concrete (N32)$^1$</td>
<td>7.79%</td>
<td>52.28%</td>
<td>78.73%</td>
</tr>
<tr>
<td>Suspended concrete (N40)$^2$</td>
<td>0.10%</td>
<td>1.86%</td>
<td>6.02%</td>
</tr>
<tr>
<td>Concrete on Ground (N20)$^3$</td>
<td>0.16%</td>
<td>4.54%</td>
<td>16.63%</td>
</tr>
<tr>
<td>Window</td>
<td>3.78%</td>
<td>19.48%</td>
<td>48.68%</td>
</tr>
<tr>
<td>Steel reinforcement</td>
<td>0.48%</td>
<td>13.48%</td>
<td>44.48%</td>
</tr>
<tr>
<td>Timber formwork</td>
<td>0.17%</td>
<td>0.47%</td>
<td>1.36%</td>
</tr>
<tr>
<td>Plasterboard</td>
<td>0.41%</td>
<td>2.20%</td>
<td>9.23%</td>
</tr>
</tbody>
</table>

The variations associated with the other building materials were less than 1%.
1. Grade N40 used in the vertical structural elements such as columns and shear walls.
2. Grade N32 used in the slabs.
3. Grade N20 used in the other concrete element (staircase).

4. **Investigate the relative contribution that types of structural concrete and types of slab have on the lifetime energy demand and thermal performance of office buildings;**
The results of the energy simulation (section 6.4.2) showed that the thermal energy performance of the building was influenced by different forms of structural materials, and the thermal capacity of concrete construction forms can be utilised to shift thermal loads (sections 6.4.3 and 6.4.4), reduce peak demand, and reduce operational energy consumption. The selection of an appropriate concrete type was more important in terms of energy performance in the coldest (Melbourne and Canberra) and hottest (Darwin) climate zones of this PhD.

**Key findings**

- Energy consumption across all five climate zones shows that a lightweight office building (called Waffle.low) with a lower thermal conductivity concrete (Ultra-lightweight concrete) required 5% more energy (up to 9.6 kWh/m² per year) than the other buildings (section 6.4.2).

- The variations in indoor and outdoor air temperatures for the different building designs during the winter design week indicated that the Ultra-lightweight concrete structure had a substantially higher peak indoor air temperature (almost 2°C) which is undesirable in hot or mild climate zones (section 6.4.4).

- The discomfort degree hours (DDH) were almost 5% higher in the building characterised with Ultra-lightweight concrete across all climates during the summer design week (Table 6-10).

- Buildings made from Ultra-lightweight concrete respond to temperature and heat flux stimulation faster, which causes overheating for most of the year.

- The thermal performance of the studied building have been more effected by type of concrete than the construction system (Figure 6-8 to 6-17), and use of Ultra-lightweight concrete in construction systems may require
alternative methods to mitigate the decreased thermal performance of buildings.

5. **Develop a life cycle assessment model of several office buildings as benchmark buildings. Propose a global assessment parameter as the results of whole life, CO₂-e emissions, and structural costs during the lifetime of buildings.**

The developed life cycle assessment method was applied to the benchmark building to identify the lifetime CO₂-e emissions costs associated with two construction systems (Flat slab and Waffle slab) and two structural materials (Normal concrete and Ultra-lightweight concrete). The results showed that the office building designed with lightweight construction method (Waffle slab) and normal concrete (Normal weight) had a lower life cycle cost (50-year lifespan) than the other design alternatives across the five climate zones in Australia. It was found that selecting the appropriate construction forms and type of concrete can save on the total costs (life cycle cost and CO₂-e emissions cost) of the building across all five major cities. It was also found that an appropriate building design can save up to 7% in material use, 5% of total energy consumption, and 5% in life cycle CO₂-e emissions.

**Key findings**

- The Lightweight structures designed with Ultra-lightweight concrete had higher lifetime CO₂-e emissions and environmental costs (up to 5.5%) than the other design alternatives, whereas the Lightweight structure made from Normal weight concrete (Waffle.Normall) had the lowest CO₂-e emissions and environmental costs (sections 7.4.1 and 7.4.2).
- The results in section 7.4.3 showed that selecting the appropriate forms of construction and type of concrete could save 2.4% of the running costs (during lifetime) for the building in Darwin and 5% for the other cities (Brisbane, Sydney, Melbourne, and Canberra).

- The developed global assessment parameter (whole life environmental and life cycle cost assessment) revealed that the Waffle slab with a right type of concrete (Normal Weight) can save up to $156 per m² (average value across all cities) in the total life cycle cost of the building across all five cities.

- The global assessment parameter (whole life cost of the buildings) showed that using Ultra-light weight concrete in the Flat slab increased the total cost of the building by almost 3% compared to Normal weight (conventional) concrete. The lightweight structure consisting of Ultra-lightweight concrete had a higher initial capital cost and a higher demand for more operational energy (as shown in 7.4.3) during the lifetime of the building and as a result, had a higher environmental impact than the other design alternatives. From a structural design perspective, it is worth looking beyond the structural system to incorporate the potential long term impact that the selection of construction materials has on the decision making process.

- The comparison between the type of structure (Waffle slab and Flat slab), which included Normal weight concrete, revealed that a lightweight structure with Normal weight concrete (Waffle.normal) can consistently save up to 2% in the total cost of a building. While both systems have similar operating energy costs, the Waffle slab has a lower environmental and initial capital costs due to using less concrete in the structural system.
8.4 Contributions of the Research Findings

From a low CO$_2$-e emissions structural design perspective, it is useful to understand how structural systems and materials can influence the lifetime performance of a building. Several databases (section 2.9), tools (section 2.6.3) and standards (sections 2.6.1, 2.6.2 and 2.6.3) exist to quantify the life cycle impact of building materials and systems, but until now, there has been almost no comprehensive life cycle assessment of the structural design and construction materials; this research therefore addresses that knowledge gap by achieving the following goals.

(i) The potential environmental impact and thermal performance of concrete.

The findings of Chapter 4 add to our understanding of the embodied CO$_2$-e emissions associated with different concrete design mixes by considering the emissions for each ingredient. The table compiled for this study (Table 4.3) addresses the effects of concrete materials in an Australian context, so now structural engineers can select an appropriate concrete mix to minimise its embodied CO$_2$-e emissions in Australia.

This research concludes that the embodied carbon assessment associated with the properties of concrete varies for different inventory databases. The summarised results of section 4.2 (Figure 4.9 and Figure 4.10) provide a quantified comparisons across different databases that can be used as a research tool where these databases are used.

(ii) An uncertainty analysis of the life cycle environmental impact of building materials
The literature review highlighted (sections 2.10 and 5.3) the complexity associated with applying a life cycle assessment to the building sector because buildings have a very long lifetime (more than 50 years); it is therefore a challenging task to predict the whole of lifetime impact of a project from “Cradle to Grave”. Chapter 5 provides an uncertainty analysis method to model the variations associated with the lifetime CO2-e emissions of a building, the results of this which will provide the contribution and magnitude of changes associated with the CO2-e emissions of the most intensive building material over a building’s lifetime. It was found that the selection of concrete, the type of windows and the amount of steel reinforcement had the maximum impact on the overall embodied CO2-e emissions across all four building structures. Moreover, the established data in Section 5.5 provides a reference point and guidelines for future studies to compare how their system performance compared to the benchmark office building.

(iii) Potential impact of structural materials on the energy and thermal performance of buildings

The ongoing development of more novel construction materials such as Ultra-lightweight concrete, which combines moderate thermal insulation with the load-bearing capacity raises a question about their potential impact on the thermal mass of a building. Hence the effect of new materials on the overall energy performance of a real building during its operational phase merits study. This part of the work points out the importance of a
holistic approach to look beyond the designed structural system and evaluate its impact over the lifetime of a building.

One of the major contributions of this research is the subsequent development and application of a simulation based assessment that Ultra-lightweight concrete has on the overall energy performance of a benchmark building. Energy analysis and thermal performance was used to investigate the impact of selecting the type of concrete (Normal and Ultra-lightweight) and structural systems on the overall indoor comfort and energy performance of a benchmark office building in Australia. The energy analysis estimated the effect that the form of construction and structural materials had on the thermal energy performance of the building. The association between thermal capacity and concrete structure can be used to decrease the operational energy demand, reduce the peak load, and shift the thermal loads. Selecting the appropriate type of concrete was more important in terms of energy performance in the coldest (Melbourne and Canberra) and hottest (Darwin) climate zones of this study.

(iiv) Develop an assessing tool to quantify the lifetime CO₂-e emissions associated with different structural design alternatives of buildings.

This research develops a framework for the life cycle CO₂-e emissions of the structural design of buildings and a method to demonstrate how different structural solutions and materials affect lifetime energy consumption, CO₂-e emissions, and costs in a building. This framework addresses the lifetime effects of structural decision as a single economic value. It was shown that an appropriate structural design can
reduce the cost of material usage (by 7%), the operational energy demand (by 5%), and the CO₂-e emissions impacts (by 5%). This framework can be used as a supporting decision making tool to select the most efficient structural materials and methods of construction over the lifetime of the building.

The research undertaken in this thesis provides a quantitative method that will enable structural engineers to integrate life cycle building performance and emissions awareness into the decision making process; it also proposes a framework to assess the efficiency of structural alternatives over a lifetime whilst simultaneously considering the environmental impact of the initial design. During this research, some observations pointed out the need for further research in this field which would enhance our knowledge of the low CO₂-e emissions structural design of buildings.

8.5 Recommendations for further research

The previous sections investigated the potential impact that structural materials and types of construction have on the life cycle CO₂-e emissions of an office building. This investigation used a benchmarking method to compare the impact of different design alternatives (various types of concrete and construction systems), but the potential impact of structural design on other aspects of sustainable building design were outside the scope of this PhD.

There are also several areas for further development and applications for the work undertaken in this thesis. The framework developed in this PhD to assess lifetime environmental impacts and costs associated with different structural solutions was applied to a benchmark office in Australia, but it could usefully be applied to assess other types of buildings. This PhD examined two aspects of structural design over the
whole life cycle of a building, the floor systems (slab thickness) in various systems of construction, and different types of concrete (low density and high density). A similar approach could be used to assess the potential effect of structural design on various types of buildings by considering alternative framing systems and materials such as a cross laminated timber system.

The benchmark office building in this research is one of four benchmark buildings proposed by National Standard Development Organization (NS11401.1 2014), of which far too little attention has been given to the other three. Considering the potential effect that structural systems have on the lifetime performance of various buildings can help in understanding possible future development in their sustainable structural design. It is recommended that the impact of structural design solutions be considered on the other archetype benchmark buildings, as proposed by NS11401.1 (2014), in order to enhance our understanding of how structural engineering promotes the demonstrated advantages of sustainable tools.

The levels of uncertainty associated with estimating the life cycle performance of buildings might be further investigated by incorporating the cost uncertainty associated with the structural design of buildings. The cost uncertainty incorporates the variations associated with structural solutions, rehabilitation measures, and the expected losses that might happen during the lifetime of a building for each defined limit states (Tsimplokoukou et al. 2014). The uncertainties associated with structural design can include hazard uncertainties (such as wind loads), structural uncertainties (such as structural capacity, materials properties and stiffness), and interaction mechanism uncertainties (such as the duration of pressure levels (Tsimplokoukou et al. 2014). Integrating these developed life cycle assessment methods (as proposed in
Chapter 7) with structural performance assessment method could improve the sustainability aspects of building design.

Finally, the continuing development of more novel construction materials raises a concern about their potential impact on the lifetime performance of buildings. This PhD has shown the potential impact of novel construction materials (Ultra-lightweight concrete) on the lifetime performance of a benchmark building; it also provides a base for developing a labelling model to compare the total CO\textsubscript{2}e emissions of materials and to demonstrate its comparative performance against the benchmark data; a labelling method can also help structural engineers realise the ecological impact and potential lifetime performance of a material in a simple and clear manner.

8.6 Summary

This thesis set out to evaluate the impact that a structural system and construction materials have on the sustainability of buildings. A core part of this thesis was based on the sequence of papers (Chapters 4-7) already published or accepted for publication. This research mainly emphasised the life cycle analysis of a building while measuring the effects that design solutions have on the environment over its whole lifetime, from Cradle to Grave.

Returning to the question posed at the beginning of this PhD, it is now possible to state that structural engineering can contribute to the sustainability of buildings by understanding the long term characteristics and limitations of alternative designs at a global scale before selecting an appropriate design.
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Appendix A: Mix properties of different batches of concrete

This appendix contains details of 90 different concrete design mixes that were used as part of Chapter 4. Table A-1 shows the mix properties of different batches of concrete collected from 8 published journal papers and databases.

Table A-1 Mix properties of different batches of concrete

<table>
<thead>
<tr>
<th>Mix Number</th>
<th>Binder (kg/m³)</th>
<th>Aggregates (kg/m³)</th>
<th>Administer (liter)</th>
<th>Water (kg/m³)</th>
<th>ECE (m³/m³)</th>
<th>CO₂ bounce (% CCE)</th>
<th>Conductivity (W/mK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>32</td>
<td>175</td>
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<td>846</td>
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270
Appendix B: Detailed structural design

This appendix summarises the structural design of the benchmark buildings. The information in this section has been categorised into a summary of the design for Flat slab and Waffle slab (section B-1), Manual hand calculation and versifications for Flat slab (section B-2), and typical concrete column design (CAD and Excel spread sheet output) in section B-3.

Section B-1: Summary of a detailed structural design

A summary of the Flat slab detailed structural design is provided in Table B-1.

Table B-1 Flat slab detailed structural design

<table>
<thead>
<tr>
<th>Structure elements</th>
<th>Size of element (Cross section) (mm)</th>
<th>Grade of concrete</th>
<th>Steel arrangement (Cross section) (mm)</th>
<th>Number of Columns</th>
<th>Quantity of Concrete (m$^3$)</th>
<th>Total Concrete (m$^3$)</th>
<th>Quantity of Steel (tonne)</th>
<th>% Steel</th>
<th>Total Steel (tonne)</th>
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</thead>
<tbody>
<tr>
<td>Column</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Level 1 to 3</td>
<td>Interior 500x500</td>
<td>N40</td>
<td>10 N 32</td>
<td>24</td>
<td>20</td>
<td>18</td>
<td>3%</td>
<td>83</td>
<td></td>
</tr>
<tr>
<td></td>
<td>perimeter 350x350</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Level 4 to 6</td>
<td>Interior 400x400</td>
<td></td>
<td>10 N 28</td>
<td>24</td>
<td>13</td>
<td>13</td>
<td>4%</td>
<td>83</td>
<td></td>
</tr>
<tr>
<td></td>
<td>perimeter 325x325</td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Level 7 to 9</td>
<td>Interior 375x375</td>
<td></td>
<td>10 N 20</td>
<td>24</td>
<td>11</td>
<td>9</td>
<td>2%</td>
<td>63</td>
<td></td>
</tr>
<tr>
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<td>perimeter 300x300</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Level 10 to 12</td>
<td>Interior 375x375</td>
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<td>8 N 24</td>
<td>24</td>
<td>8</td>
<td>8</td>
<td>3%</td>
<td>63</td>
<td></td>
</tr>
<tr>
<td></td>
<td>perimeter 300x300</td>
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<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Level 13 to 15</td>
<td>Interior 275x275</td>
<td></td>
<td>6 N 16</td>
<td>24</td>
<td>6</td>
<td>2</td>
<td>3%</td>
<td>63</td>
<td></td>
</tr>
<tr>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Slab</td>
<td>Suspended floor with drop panel</td>
<td>N32</td>
<td>Column strip &amp; Mid span: Top- N12@150 mm; Bot- N12@100 mm (Same for both directions) + Drop panel (N12@ 300 mm)</td>
<td>2469</td>
<td>3,000</td>
<td>654</td>
<td>0.56%</td>
<td>654</td>
<td></td>
</tr>
<tr>
<td>Wall</td>
<td>200 mm (thickness)</td>
<td>N40</td>
<td>N12@300 mm both sides (Top &amp; Bottom)</td>
<td>---</td>
<td>31</td>
<td>9</td>
<td>4%</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Staircase</td>
<td>15 mm (thickness)</td>
<td>N20</td>
<td>N12@200 mm both directions</td>
<td>---</td>
<td>250</td>
<td>7</td>
<td>1%</td>
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</table>
Table B-2 provides a summary of Waffle slab detailed structural design.

### Table B-2 Waffle slab detailed structural design

<table>
<thead>
<tr>
<th>Column</th>
<th>Structure details- Waffle Slab</th>
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<tbody>
<tr>
<td></td>
<td>Structure elements</td>
</tr>
<tr>
<td>Level 1 to 3</td>
<td>Interior</td>
</tr>
<tr>
<td></td>
<td>perimeter</td>
</tr>
<tr>
<td>Level 4 to 6</td>
<td>Interior</td>
</tr>
<tr>
<td></td>
<td>perimeter</td>
</tr>
<tr>
<td>Level 7 to 9</td>
<td>Interior</td>
</tr>
<tr>
<td></td>
<td>perimeter</td>
</tr>
<tr>
<td>Level 10 to 12</td>
<td>Interior</td>
</tr>
<tr>
<td></td>
<td>perimeter</td>
</tr>
<tr>
<td>Level 13 to 15</td>
<td>Interior</td>
</tr>
<tr>
<td></td>
<td>perimeter</td>
</tr>
<tr>
<td>Slab</td>
<td></td>
</tr>
<tr>
<td>Suspended floor</td>
<td></td>
</tr>
<tr>
<td>Drop panel</td>
<td></td>
</tr>
<tr>
<td>Stem</td>
<td></td>
</tr>
<tr>
<td>Staircase</td>
<td></td>
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<tr>
<td>Staircase</td>
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</table>
Section B-2: Manual calculation and verification for flat of slab

This section provides details of the manual calculation verification for Flat slabs. All the design calculations for the reinforced slabs comply with the Australian standards, including: Concrete structure (AS3600 2009) and Structural Actions (AS/NZ1170.1 2002).

Applied load:

For the suspended office floor:

Self-weigh (SW): 25 kPa (by considering concrete as Normal weight with steel reinforcement)

Additional Dead load (ADL): 0.5 kPa (for permanent services and fixtures)

Live load (LL): 3.0 kPa (AS/NZ1170.1 (2002), Clause 3.4.1)

The strength of concrete was $f'c = 32$ MPa for the slabs, and the maximum size bars were 16 mm diameter.

Reinforced Flat slab

Minimum slab thickness (depth)

Based on the Australian standard (AS3600 2009), the clear cover required to meet fire resistance and durability was 35mm, that also includes a construction tolerance (5mm). The thickness of the preliminary slab was selected by using the Cement and Concrete Association of Australia guidelines (CCAA 2003). Although this guideline is based on an older version of AS3600 (2001), it has a good preliminary point to determine the required depth of the slab.

Span= 5.27m, LL=3.0 kPa based on the graph on page 15 (CCAA 2003) that gives the first trial D as 170 mm.

The depth of slab can be controlled by the deflection limit:
\[
\frac{L_{ef}}{d} \leq k_3 k_4 \left[ \left( \frac{\Delta}{L_{ef}} \right) \frac{1000 E_c}{F_{d,ef}} \right]^{\frac{1}{3}}
\]

(AS 3600, Clause 9.3.4.1)

Where:

\(D=170\text{mm}\)

\(SW=25 \times 0.17=4.25\text{ kPa}\)

\(DL=4.25+0.5=4.75\text{ kPa}\)

\(LL=3\text{ kPa}\)

\(L_{ef} = \min [L_n + D; L] = [(5270 - 500) + 170; 5270] = 4940\text{mm}\)

\(k_3 = 0.95\) for two way flatslab without drop panel (AS 3600, Clause 9.3.4.1)

\(k_4 = 0.75\) – Exterior span (AS 3600, Clause 9.3.4.1)

\[
\frac{\Delta}{L_{ef}} = \frac{1}{250} \text{ - Total deflection}
\]

(AS 3600, Table 2.3.2)

\[
\frac{\Delta}{L_{ef}} = \frac{1}{500} \text{ - Incremental deflection}
\]

(AS 3600, Table 2.3.2)

\(E_c = 30100\text{ MPa}\)

\(\psi_s = 0.7\) (AS 1170.0:20, Table 4.1)

\(\psi_i = 0.4\) (AS 1170.0:20, Table 4.1)

\(\psi_c = 0.4\) (AS 1170.0:20, Table 4.1)

\(k_{cs} = [2.0 - 1.2 (A_{sc}/A_{st})] \geq 0.8\) (AS 1170.0:20, Table 4.1)

\(= 2\) (assumed \(A_{sc}=0\) for most critical case)

\(F_{d,ef} = (1 + k_{cs})g + (\psi_c + k_{cs} \times \psi_i)q\) - Total deflection

(AS 3600, Clause 9.3.4.1)
\[ \begin{align*}
&= (1 + 2) \times 4.75 + (0.7 + 2 \times 0.4) \times 3 \\
&= 18.75 \text{ kPa} \\
F_{d,ef} &= (k_{cs} \times g) + (\psi_c + k_{cs} \times \psi_i)q \\
&= (2 \times 4.75) + (0.7 + 2 \times 0.4) \times 3 \\
&= 14 \text{ kPa}
\end{align*} \]

**Total deflection:**

\[
\frac{L_{ef}}{d} \leq k_3k_4 \left[\frac{\left(\frac{\Delta}{L_{ef}}\right)1000 E_c}{F_{d,ef}}\right]^{\frac{1}{3}}
\]

\[
\frac{L_{ef}}{d} \leq 0.95 \times 1.75 \times \left[\frac{\left(\frac{1}{250}\right) \times 1000 \times 30100}{18.75}\right]^{\frac{1}{3}}
\]

Then \( d \approx \frac{4940}{30.90} = 159.87 \text{ mm} \)

**Incremental deflection:**

\[
\frac{L_{ef}}{d} \leq k_3k_4 \left[\frac{\left(\frac{\Delta}{L_{ef}}\right)1000 E_c}{F_{d,ef}}\right]^{\frac{1}{3}}
\]

\[
\leq 0.95 \times 1.75 \times \left[\frac{\left(\frac{1}{500}\right) \times 1000 \times 30100}{14}\right]^{\frac{1}{3}}
\]

Then

\( d \approx \frac{4940}{27.03} = 182.75 \text{ mm} \)

Therefore, incremental deflection governs the minimum slab thickness. Since there will be steel reinforcement in both directions (X and Y), the minimum slab thickness is:
D = d+ cover+ ½ bar thickness (X axis) + bar thickness (Y axis).

\[ D = 182.75 + 35 + \frac{12}{2} + 12 = 235.75 \text{ mm} \]

Revision of the design is necessary and several alternatives were considered:

1. Use a drop panel, then \( K3 = 1.05 \) (AS 3600, Clause 9.3.4.1)
2. Use \( A_{sc} \) in the design process, then \( k_{cs} = 1 \)

Recheck the calculations to satisfy the ratio of span over thickness by considering new assumptions

\[ D = 200 \text{ mm} \]

\[ L_{ef} = [(5270 - 500) + 200; 5270] = 4970 \text{ mm} \]

\[ F_{d,ef} = (k_{cs} \times g) + (\psi_c + k_{cs} \times \psi_d)q \text{ Incremental deflection} \]

\[ = (1 \times 4.75) + (0.7 + 2 \times 0.4) \times 3 \]

\[ = 8.75 \text{ kPa} \]

\[
\frac{L_{ef}}{d} \leq k_3 k_4 \left[ \left( \frac{\Delta}{L_{ef}} \right) \frac{1000 E_c}{F_{d,ef}} \right]^{\frac{1}{3}}
\]

\[ \leq 1.05 \times 1.75 \times \left[ \left( \frac{1}{500} \right) \times 1000 \times 30100 \right]^{\frac{1}{3}} \]

Then \( d = \frac{4970}{34.30} = 144.89 \text{ mm} \)

\[ D = 144.89 + 35 + \frac{12}{2} + 12 = 197.89 \text{ mm} \approx 200 \text{ mm} \therefore \text{Ok} \]

\( d_x = 200 - 35 - \frac{12}{2} = 159 \text{ mm} \)

\( d_y = 200 - 35 - \frac{12}{2} - 12 = 147 \text{ mm} \)
Correct the applied load:

D = 200mm

SW = 25 × 0.2 = 5 kPa

DL = 5 + 0.5 = 5.5 kPa

LL = 3 kPa

Determine the bending moment:

Since the slab is symmetrical, only one direction was calculated to represent the process of design and analysis. Moreover, the bending moments and strip dimensions are equal in both axes (X and Y), so the bending moments were determined using the Simplified method.

Design bending moment and reinforcement in the long span direction:

Design strips:

Figure B-1 shows the dimensions and layout of the design strips.
Figure B-1 the dimensions and layout of the design strips
Table B-3 provides the design moment factors for the Flat slab supported by columns.

### Table B-3 design moment factors for the Flat slab

<table>
<thead>
<tr>
<th>Location of moment</th>
<th>Exterior moment (negative moment)</th>
<th>Mid span moment (positive moment)</th>
<th>Interior moment (negative moment)</th>
</tr>
</thead>
<tbody>
<tr>
<td>End span</td>
<td>0.25</td>
<td>0.5</td>
<td>0.75</td>
</tr>
<tr>
<td>Interior span</td>
<td>------</td>
<td>0.35</td>
<td>0.65</td>
</tr>
</tbody>
</table>

Reference: AS3600 (2009), Table 6.9.5.3, Table 6.1.4.3

Table B-4 provides the distribution of bending moments to the column strip.

### Table B-4 distribution of bending moments to the column strip

<table>
<thead>
<tr>
<th>Span number</th>
<th>Distribution of bending moments to the column strips</th>
<th>Left side/end</th>
<th>Mid-span</th>
<th>Right side/end</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>1.00</td>
<td>0.6</td>
<td>0.75</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>0.75</td>
<td>0.6</td>
<td>0.75</td>
</tr>
<tr>
<td>3</td>
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<td>0.75</td>
<td>0.6</td>
<td>0.75</td>
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<tr>
<td>4</td>
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<td>0.75</td>
<td>0.6</td>
<td>0.75</td>
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<tr>
<td>6</td>
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<td>0.75</td>
<td>0.6</td>
<td>1.00</td>
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</tbody>
</table>

**Edge Design Strip**

\[ F_d = 1.2 \times (5.5) + 1.5 \times (3) = 11.1 \text{ kPa} \]

Design length \( L_T = 5.27 \text{ m} \)

\[ L_o = L - 0.7a_{sup, L} - 0.7a_{sup, R} \]  
(AS 3600, Clause 9.3.4.1)

\[ a_{sup} = \text{(Column size/2)} + \text{(thickness of drop panel)} = (550/2) + (260-200) = 335 \text{ mm} \]

\[ L_o = 5270 - 0.7 \times 335 = 5035 \text{ mm} \approx 5.04 \text{ m} \]

\[ M_o = \frac{F_d \times L_T \times L_o^2}{8} \]  
(AS 3600, Clause 6.10.4.2)

\[ M_o = \frac{11.1 \times 5.27 \times 5.04^2}{8} = 185.73 \text{ kN.m} \]
Design Moments:

TableB-3 summarises the design moments for the end span - Edge design strip

<table>
<thead>
<tr>
<th></th>
<th>Exterior moment (negative moment): 0.25(M_o)</th>
<th>Mid span moment (positive moment): 0.5(M_o)</th>
<th>Interior moment (negative moment): 0.75(M_o)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(-46.43) kN.m</td>
<td>92.86 kN.m</td>
<td>(-139.29) kN.m</td>
</tr>
<tr>
<td>column strips</td>
<td>Middle strips (1.00)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-46.43 kN.m</td>
<td>0 kN.m</td>
<td>55.71 kN.m</td>
<td>37.14 kN.m</td>
</tr>
<tr>
<td>Middle strips</td>
<td>Middle strips (0.6)</td>
<td>Middle strips (0.4)</td>
<td>Column strips (0.75)</td>
</tr>
<tr>
<td>0 kN.m</td>
<td></td>
<td></td>
<td>Column strips (0.25)</td>
</tr>
<tr>
<td></td>
<td>55.71 kN.m</td>
<td>37.14 kN.m</td>
<td>(-104.46) kN.m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(-34.82) kN.m</td>
</tr>
</tbody>
</table>

TableB-6 summarises the design moments for the interior span - Edge design strip

<table>
<thead>
<tr>
<th></th>
<th>Exterior moment (negative moment): 0.65(M_o)</th>
<th>Mid span moment (positive moment): 0.35(M_o)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(-120.72) kN.m</td>
<td>65 kN.m</td>
</tr>
<tr>
<td>Column strips</td>
<td>Middle strips (0.75)</td>
<td>Middle strips (0.25)</td>
</tr>
<tr>
<td>-90.54 kN.m</td>
<td>-30.18 kN.m</td>
<td>39 kN.m</td>
</tr>
<tr>
<td>Middle strips</td>
<td>Middle strips (0.6)</td>
<td></td>
</tr>
<tr>
<td>0 kN.m</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Interior Design Strip

\[ F_d = 1.2 \times (5.5) + 1.5 \times (3) = 11.1 \text{ kPa} \]

Design length \(L_T = 5.27 \text{ m}\)

\[ L_o = L - 0.7a_{\text{sup}, L} - 0.7a_{\text{sup}, R} \]

\(a_{\text{sup}} = \frac{\text{Column size}}{2} + \text{thickness of drop panel} = \frac{550}{2} + 2 \times (260 - 200) = 395 \text{ mm} \)

\[ L_o = 5270 - 0.7 \times 395 = 4993.5 \text{ mm} \approx 5 \text{ m} \]

\[ M_o = \frac{F_d \times L_T \times L_o^2}{8} \]

\(\text{(AS 3600, Clause 9.3.4.1)}\)

\(\text{(AS 3600, Clause 6.10.4.2)}\)
\[ Mo = \frac{11.1 \times 5.27 \times 5^2}{8} = 182.80 \text{ kN.m} \]

**Design Moments:**

Table B-7 summarises the design moments for the end span - Edge design strip

<table>
<thead>
<tr>
<th>Exterior moment (negative moment): 0.25Mo</th>
<th>Mid span moment (positive moment): 0.5Mo</th>
<th>Interior moment (negative moment): 0.75Mo</th>
</tr>
</thead>
<tbody>
<tr>
<td>-45.7 kN.m</td>
<td>91.4 kN.m</td>
<td>-137.1 kN.m</td>
</tr>
<tr>
<td>column strips (1.00)</td>
<td>Middle strips (0)</td>
<td>column strips (0.6)</td>
</tr>
<tr>
<td>-45.7 kN.m</td>
<td>0 kN.m</td>
<td>54.84 kN.m</td>
</tr>
</tbody>
</table>

Table B-8 summarises the design moments for the interior span - Edge design strip

<table>
<thead>
<tr>
<th>Exterior moment (negative moment): 0.65Mo</th>
<th>Mid span moment (positive moment): 0.35Mo</th>
</tr>
</thead>
<tbody>
<tr>
<td>-118.82 kN.m</td>
<td>63.98 kN.m</td>
</tr>
<tr>
<td>column strips (0.75)</td>
<td>Middle strips (0.25)</td>
</tr>
<tr>
<td>-89.11 kN.m</td>
<td>-29.70 kN.m</td>
</tr>
</tbody>
</table>

Figure B-2 provides the bending moments measured in kNm
Figure B-2 Bending moment plan for Flat slab, $f'c = 32$MPa
Reinforcement

In the previous section, the negative bending moments at the supports and positive bending moments at the mid-span were determined and then distributed into the column strip and middle strip.

The following section provides a sample calculation for the reinforcement required to resist a bending moment in the Y direction. The remaining calculation to determine the steel reinforcement in both directions was calculated by using the Excel spreadsheet and SAFE software.

Data:

For this design, N16 bars were used as the main distribution reinforcement.

$F_{sy} = 500$ MPa, $A_{s} = 200$ mm$^2$

At mid-span:

$d_s = 200-35-16/2 = 157$ mm

At mid-span = $+M^* = 55.71$ kN.m

$$\rho_{min} = 0.24 \left( \frac{D_s}{d} \right)^2 \left( \frac{f_{ct}}{f_{sy}} \right)$$

$$= 0.24 \left( \frac{200}{157} \right)^2 \times \frac{3.4}{500} = 0.00264$$

Minimum reinforcement required for shrinkage and temperature effect:

$$\rho \geq 0.75 \times 0.0035(bD_s)/(bd)$$

$$\geq 0.75 \times 0.0035(200)/(157) = 0.0033$$

Therefore the shrinkage and temperature reinforcement governs:

$A_{s} = 0.75 \times 0.0035 \times bD_s = 0.75 \times 0.0035 \times 1000 \times 200 = 525$ mm$^2$/m

For 2.635 m: $525 \times 2.635 = 1383.38$ mm$^2$
Check the capacity of the section with this reinforcement

\[ \phi M_u = 0.8 \times f_{sy} \times (0.925d) \]

\[ = (0.8 \times 1383.38 \times 500 \times 0.925 \times 157) = 80.36 \text{ kN.m} \]

Using N16 has too much space between the bars so change them to N12.

Hence, N12 @ 150 mm cts.

**At First Interior Column:**

Dx= 200+60 (drop panel)= 260

dx= 260-35-(16/2)= 217 mm

At mid-span= +M*=-102.82 kN.m

\[
\rho_{min} = 0.24 \left( \frac{D_s}{d} \right)^2 \left( \frac{f_{ct}}{f_{sy}} \right) \quad (AS 3600, \text{Clause 9.1})
\]

\[ = 0.24 \left( \frac{260}{217} \right)^2 \times \left( \frac{3.4}{500} \right) = 0.00234 \]

Minimum reinforcement required for the shrinkage and temperature effects:

\[ \rho \geq 0.75 \times 0.0035(bDs)/(bd) \quad (AS 3600, \text{Clause 9.4.3}) \]

\[ \geq 0.75 \times 0.0035(260)/(217) = 0.0031 \]

Therefore shrinkage and temperature reinforcement governs:

\[ A_{st} = 0.75 \times 0.0035 \times bDs = 0.75 \times 0.0035 \times 1000 \times 250 = 656.25 \text{ mm}^2/\text{m} \]

For 2.635 m: 656.25 \times 2.635= 1726.21 mm$^2$

Check the capacity of the section with this reinforcement

\[ \phi M_u = 0.8 \times f_{sy} \times (0.925d) \]

\[ = (0.8 \times 1383.38 \times 500 \times 0.925 \times 217) = 111.07 \text{ kN.m} \]

Using N16 has too much space between the bars so change them to N12.

Hence, N12 @ 100 mm cts.
Punching shear design

The punching shear is checked on a critical section at a distance of \( d_{om}/2 \) from the face of the support (AS 3600 Clause 9.2.1.1). For rectangular columns and concentrated loads, the critical area is taken as a rectangular area with the sides parallel to the sides of the columns or the point loads (AS 9.2.1.3). The following Figure B-3 represents the punching perimeters considered by AS 3600 (2009).

![Figure B-3 the punching perimeters considered by AS 3600 (2009).](image)

The shear capacity \( f_{cv} \) was calculated based on the lower of two expressions from AS 3600, Clause 9.2.3, as shown below:

\[
f_{cv} = \min \left\{ 0.17 \left(1 + \frac{2}{\beta_h}\right)\sqrt{f'_c}, \frac{0.34}{\beta_h}\sqrt{f'_c} \right\} \quad \text{(AS 3600, Clause 9.2.3)}
\]

\( \beta_h \) is the ratio of the longest dimension to the shortest dimension of the critical section=1

\[
f_{cv} = \min \left\{ 0.17 \left(1 + \frac{2}{1}\right)\sqrt{32} = 2.88\right\} = 1.92
\]

From Table 4.4 (Warner et al. 2010), the out of balance moment between two adjacent faces of the first interior column is:

\[
M_V = (\text{coefficient} \times M_o)_{\text{end span}} - (\text{coefficient} \times M_o)_{\text{internal span}}
\]

(Warner et al. (2010), Page 253)
\[ M_V^* = (0.75 \times 185.73) - (0.65 \times 182.80) = 22.85 \text{ kN.m} \]

This is equal to the out of balance moments on each side of the interior column in x direction, which is shown in Figure B-2.

\[ M_V^* = (102.82 + 34.27 + 34.27) - (89.11 + 29.70 + 29.70) = 22.85 \text{ kN.m} \]

The minimum bending moment to be transmitted is:

\[ M_V^* = 0.06 \left( \frac{1.2DL + \frac{1.5LL}{2}}{L_tL_0^2} \right) \left( 1.2DL - 1.2DL L_tL_0^2 \right) \]

(Warner et al. (2010), Equation 4.15)

\[ M_V^* = 0.06 \left( 1.2 \times 5.5 + \frac{1.5 \times 3}{2} \right) 5.27 \times 5.04^2 - 1.2 \times 5.5 \times 5.27 \times 5^2 \]

\[ M_V^* = 0.06(1184.71 - 869.55) = 18.91 \text{ kN.m} \]

The corresponding load to be transferred by the punching shear

Tributary Area = 5.27 \times 5.27 = 27.77 \text{ m}^2

Punching force \( V^* = 11.1 \times 27.77 = 308.247 \text{ kN} \)

\[ d_{om} = \frac{dx + dy}{2} \]

dy: Thickness of slab with drop panel=200+60 = 260 mm

dx: dy- bar thickness (N12)= 260-12= 248 mm

\[ d_{om} = \frac{260 + 248}{2} = 254 \text{ mm} \]

\[ V_{uo} = ud_{om}f_{cv} \]

(Warner et al. (2010), Equation 4.16)

for interior column

\[ U = \text{column thickness} + \left( \frac{d_{om \times axis}}{2} \right) \times 2 + \left( \frac{d_{om \times y axis}}{2} \right) \times 2 \]

\[ u = 550 + 254 \times 2 = 1058 \text{ mm} \]

\[ V_{uo} = 1058 \times 254 \times 1.92 \times 10^{-3} = 515.96 \text{ kN} \]
\[
\phi V_u = \frac{\phi V_{uo}}{1 + \frac{M_V}{u} \left( \frac{a}{8V^* d_{om}} \right)}
\]

\[
\phi V_u = \frac{0.7 \times 515.96}{22.85} = 361.15 \text{ kN}
\]

\[
(1 + \frac{550 + 254}{(8 \times 308.247 \times 254)/1058})
\]

\[
\phi V_u > V^*
\]

\[
361.15 \text{ kN} > 308.247 \text{ kN} \therefore \text{Ok}
\]

Hence, failure will not occur at the front face and the drop panel is enough to avoid the need for fitments.

Calculate \( V_{u.min} \):

\[
V_{u.min} = \frac{1.2 V_{uo}}{(1 + \frac{u M_V}{(2 V^* a^2)})}
\]

\[
V_{u.min} = \frac{1.2 \times 515.96}{1058 \times 22.85} = 619.114 \text{ kN}
\]

\[
\phi V_{u.min} = 0.7 \times 619.11 = 433.38 \text{ kN}
\]

\[
361.15 \text{ kN} > 308.247 \text{ kN} \therefore \text{Ok}
\]

Hence minimum reinforcement is sufficient.

Design of closed ties:

\[
y_l = a - \min \text{ cover} - \frac{d_b}{2} = (550 + 254) - 35 - \left( \frac{12}{2} \right) = 763 \text{ mm}
\]

\[
\left( \frac{A_{sw}}{S} \right) = \frac{0.2 y_l}{f_{sy,f}} \left( \frac{V^*}{\phi V_{u.min}} \right)^2 = \frac{0.2 \times 763}{500} \left( \frac{308.247}{433.38} \right)^2 = 0.154 \text{ mm}^2/\text{mm}
\]

\[
\left( \frac{A_{sw}}{S} \right) = 0.154 \text{ mm}^2/\text{mm}; \quad \text{if we use N12 As = 110 mm}^2
\]
S = 714 mm

S ≤ max (300, D)  

S ≤ max (300, 260)

S = 300 mm

Then use N12 @ 300 mm cts for the torsional strips.

Also, $\phi V_{u,max} = 3\sqrt[3]{\frac{D}{\alpha}} \geq V^*$ needs to be checked. (AS 3600, Clause 9.2.4(5))

$\phi V_{u,max} = 3 \times 433.38 \sqrt{\frac{260}{550+254}} = 739.34 \geq V^* = 308.247 \therefore O k$

Check the deflection of the slab (using simplified method): (AS 3600, Clause 9.3.3)

$\Delta_{total} = \Delta_s + k_{cs}\Delta_{s,sus}$

$\Delta_s = \left(\frac{L^2}{96 E_c I_{ef,ave}}\right) (M_L + 10M_M + M_R)$

Deflection for short-term service load

$F_s = F_{Dead} + \Psi_s F_{Live}$

$F_{s,l} = F_{Dead} + \Psi_L F_{Live}$

$F_{Dead} = 5.5 \, kPa$

$F_{Live} = 3.0 \, kPa$

$\Psi_s = 0.7$ (short term live load factor)  

$\Psi_L = 1$ (Long term live load factor)  

$F_s = 5.5 + 0.7 \times 3.0 = 7.6 \, kPa$ (short term)

$F_{s,l} = 5.5 + 1.0 \times 3.0 = 8.5 \, kPa$ (long term)

Moment at the exterior column:

$-M_s = \frac{F_s L_e L_o^2}{16} = \frac{7.6 \times 5.27 \times 5^2}{16} = 62.58 \, kN.m$
Moment at the first interior column:

\[ +M_s = \frac{F_s L_t L_o^2}{10} = \frac{7.6 \times 5.27 \times 5^2}{10} = 100.3 \text{kN.m} \]

Moment at the end of mid-span:

\[ -M_s = \frac{F_s L_t L_o^2}{14} = \frac{7.6 \times 5.27 \times 5^2}{10} = 71.52 \text{kN.m} \]

Moment in the column strip (2.63m) of the design strip and based on Table 4.5 (Warner et al. 2010)

Moment at the exterior column: \[ -M_s = 0.75 \times 62.58 = -46.93 \text{kN.m} \]

Moment at the first interior column: \[ +M_s = 0.6 \times 100.3 = 60.18 \text{kN.m} \]

Moment at the end of mid-span: \[ -M_s = 0.75 \times 71.52 = -53.64 \text{kN.m} \]

Effective second moment of the area of the column strip:

Calculation for the mid-span:

\[ I_g = \frac{bh^3}{12} = \frac{2635 \times 200^3}{12} = 1756 \times 10^6 \text{mm}^4 \]

Calculation for the interior column:

\[ I_g = \frac{bh^3}{12} = \frac{2635 \times 260^3}{12} = 3.85 \times 10^9 \text{mm}^4 \]

The section crack moment \( M_{cr} \) at the mid-span:

\[ M_{cr} = Z \left( f'_{ct,f} - \sigma_{cs} \right) \]  
\[ \sigma_{cs} = \frac{2.5p_w - 0.8p_{cw}}{1+50p_w} E_s \varepsilon_{cs}^* \]
\[ p_w = \frac{A_{st}}{db_w} \]
\[ p_{cw} = \frac{A_{sc}}{db_w} \]

\( \varepsilon_{cs}^* \): design shrinkage strain

(Warner et al. 2010, Equation 3.41)

(Warner et al. 2010, Equation 3.11)

(Warner et al. 2010, Equation 3.12)

(Warner et al. 2010, Equation 3.13)

(AS 1170.2, Table 3.1.7.2)
\[
\sigma_{cs} = \frac{2.5 \times 0.0033 - 0.8 \times 0}{1 + 50 \times 0.033} \times 200 \times 10^3 \times 700 \times 10^{-6} = 1.0\text{MPa}
\]

Mid-span

\[M_{cr} = Z\left(f'_{ct,f} - \sigma_{cs}\right)
\]

\[Z = \frac{l_o}{D/2} = 17.56 \times 10^6 \text{mm}^3\]

\[M_{cr} = 17.56 \times 10^6 \times (0.6\sqrt{32} - 0.49) = 51.01 \text{kN.m}\]

**Interior column**

\[M_{cr} = Z\left(f'_{ct,f} - \sigma_{cs}\right)
\]

\[Z = \frac{l_o}{D/2} = 29.68 \times 10^6 \text{mm}^3\]

\[M_{cr} = 29.68 \times 10^6 \times (0.6\sqrt{32} - 0.49) = 82.21 \text{kN.m}\]

For interior support since \(M_s \leq M_{cr}\) (53.64 \(\leq\) 82.21)

\[I_{ef} = 0.6 I_o = 0.6 \times 3.85 \times 10^9 = 2.31 \times 10^9 \text{mm}^4\]

For the exterior column since \(M_s \leq M_{cr}\) (62.58 \(\leq\) 82.21)

\[I_{ef} = 0.6 I_o = 0.6 \times 3.85 \times 10^9 = 2.31 \times 10^9 \text{mm}^4\]

For the mid-span since \(M_s \leq M_{cr}\) (60.18 \(\geq\) 51.01)

The second moment of area for the fully cracked section \(I_{cr}\) at the mid span is:

\[n = \frac{E_s}{E_c} = \frac{200 \times 10^3}{30100} = 6.6\] , \(nA_{st} = 6.6 \times 525 = 3465 \text{ mm}^2\)

\[1000 \times d_n \times d_n / 2 = nA_{st} \times (d-d_n)\]

\[500 d_n^2 = 3465 \times (147 - d_n)\]

\[d_n^2 + 6.912 d_n - 1.01 \times 10^3 = 0\]

\[d_n = 28.51 \text{ mm}\]

\[I_{cr} = \frac{bh^3}{3} + nA_{st}(d_x - d_n)^2\]
\[ I_{cr} = \frac{2635 \times 28.51^3}{3} + 3456(147 - 28.51)^2 = 68.87 \times 10^6 \text{ mm}^4 \]

The effective second moments of area is:

\[ I_{ef} = I_{cr}/(1 - \left(1 - \frac{l_{cr}}{l_g}\right)^2 \left(\frac{M_{cr}}{M}\right)^2) \]  
(Warner et al. (2010), Equation 3.40)

\[ I_{ef} = 68.87 \times 10^6 / (1 - \left(\frac{68.87 \times 10^6}{1756 \times 10^6}\right)^2 \left(\frac{51.01}{60.18}\right)^2) \]

\[ I_{ef} = 222.36 \times 10^6 \text{ mm}^4 \]

Thus, for the end span, the weighted average effective second moment of area is:

\[ I_{ef,ave} = 1.266 \times 10^9 \text{ mm}^4 \]

Long term deflection is given by \( \Delta_{total} = \Delta_s + k_{cs}\Delta_{s,sus} \), where \( \Delta_s \) and \( \Delta_{s,sus} \) are short term deflections due to the short span proportion of (0.79) and the loading combination of \( F_s \) and \( F_{s,l} \).

\[ \Delta_s = \left(\frac{L^2}{96E_c l_{ef,ave}}\right)(M_L + 10M_M + M_R) \]

\[ \Delta_s = \left(\frac{5270^2}{96 \times 30100 \times 1.266 \times 10^9}\right)(-46.93 + 10 \times 60.18 - 53.64) \times 10^6 \]

\[ \Delta_s = 3.805 \text{ mm} \]

\[ \Delta_{s,sus} = \frac{F_s}{F_{s,l}} \Delta_s = \frac{7.6}{8.5} \times 3.805 = 3.40 \text{ mm} \]

\[ \Delta_{incr} = k_{cs}\Delta_{s,sus} = 2 \times 3.40 = 6.80 \text{ mm} \]

\[ \Delta_{total} = \Delta_s + k_{cs}\Delta_{s,sus} = 3.805 + 6.80 = 10.60 \text{ mm} \]

Limiting deflection

\[ \Delta_{incr} = \frac{L_{ef}}{500} = \frac{5720}{500} = 11.44 \text{ mm} \]

\[ \Delta_{incr} = k_{cs}\Delta_{s,sus} = 6.80 \text{ mm} < 11.44 \text{ mm} \therefore Ok \]
\[ \Delta_{\text{total}} = \frac{L_{ef}}{250} = \frac{5720}{250} = 22.88 \text{ mm} \]

\[ \Delta_{\text{total}} = \Delta_s + k_{cs} \Delta_{s.sus} = 10.60 \text{ mm} < 22.88 \text{ mm } \therefore Ok \]

Therefore, a 200 mm deep slab is adopted with N12 @ 150 mm centres (cts) at mid span and N12 @ 100 mm at column strips.
Section B-3: Concrete column design

This part provides an overview of the basic assumptions, design preconditions, and some of the design parameters that affect the design of concrete columns; CAD software (Etabs) was used to calculate the required longitudinal steel reinforcement. The following two steps were considered when designing the reinforced concrete columns:

1- Axial force-biaxial moment interaction surfaces for all the different types of concrete sections in the model.

2- Check the Axial and Bending capacity of each column for the factored loading combinations.

The following Tables B-9 to B-16 show the sample structural analysis for a selected column in level 1.

Table B-9 Section Properties

<table>
<thead>
<tr>
<th>b (mm)</th>
<th>h (mm)</th>
<th>dc (mm)</th>
<th>Cover (Torsion) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>350</td>
<td>350</td>
<td>64</td>
<td>30</td>
</tr>
</tbody>
</table>

Table B-10 Column Element Details (Summary)

<table>
<thead>
<tr>
<th>Level</th>
<th>Element</th>
<th>Section ID</th>
<th>Combo ID</th>
<th>Station Loc</th>
<th>Length (mm)</th>
<th>LLRF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Story1</td>
<td>C2</td>
<td>350X350m (1.2DDL+1.5 LL)</td>
<td>3300</td>
<td>3300</td>
<td>0.407</td>
<td></td>
</tr>
</tbody>
</table>

Table B-11 Material Properties

<table>
<thead>
<tr>
<th>Ec (MPa)</th>
<th>f'c (MPa)</th>
<th>Lt.Wt Factor (Unitless)</th>
<th>fy (MPa)</th>
<th>fys (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>32800</td>
<td>40</td>
<td>1</td>
<td>413.69</td>
<td>413.69</td>
</tr>
</tbody>
</table>

Table B-12 Design Code Parameters

<table>
<thead>
<tr>
<th>ΦT</th>
<th>ΦC</th>
<th>ΦVns</th>
<th>ΦVs</th>
<th>ΦVjoint</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8</td>
<td>0.6</td>
<td>0.7</td>
<td>0.6</td>
<td>0.7</td>
</tr>
</tbody>
</table>

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Table B-13 Axial Force and Biaxial Moment Design For N*, M*₂, M*₃

<table>
<thead>
<tr>
<th>Design N* kN</th>
<th>Design M*₂ kN-m</th>
<th>Design M*₃ kN-m</th>
<th>Minimum M₂ kN-m</th>
<th>Minimum M₃ kN-m</th>
<th>Rebar Area mm²</th>
<th>Rebar %</th>
</tr>
</thead>
<tbody>
<tr>
<td>2657.1922</td>
<td>-46.5009</td>
<td>31.167</td>
<td>46.5009</td>
<td>46.5009</td>
<td>3016</td>
<td>2.46</td>
</tr>
</tbody>
</table>

Table B-14 Axial Force and Biaxial Moment Factors

<table>
<thead>
<tr>
<th>Major Bend(M3)</th>
<th>K_m Factor Unitless</th>
<th>δ_b Factor Unitless</th>
<th>δ_s Factor Unitless</th>
<th>K Factor Unitless</th>
<th>Length mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3300</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Minor Bend(M2)</th>
<th>K_m Factor Unitless</th>
<th>δ_b Factor Unitless</th>
<th>δ_s Factor Unitless</th>
<th>K Factor Unitless</th>
<th>Length mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.43439</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3300</td>
</tr>
</tbody>
</table>

Table B-15 Shear Design for V*₂, V*₃

<table>
<thead>
<tr>
<th>Shear V* kN</th>
<th>Shear ΦVₜₚ kN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major, V*₂</td>
<td>14.228</td>
</tr>
<tr>
<td>Minor, V*₃</td>
<td>0.8716</td>
</tr>
</tbody>
</table>

Interaction diagram:

Figure B-3 Structural design: Interaction diagram for a perimeter columns level 1-3 (Based on Etabs output)

Table B-16 Column axial load and bending moment

<table>
<thead>
<tr>
<th>Point</th>
<th>P (kN)</th>
<th>M₃ (kNm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3146.9902</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>2594.0073</td>
<td>65.5322</td>
</tr>
<tr>
<td>3</td>
<td>2286.5342</td>
<td>101.9699</td>
</tr>
<tr>
<td>4</td>
<td>1875.9332</td>
<td>130.0551</td>
</tr>
<tr>
<td>5</td>
<td>1441.5865</td>
<td>148.2139</td>
</tr>
<tr>
<td>6</td>
<td>856.3381</td>
<td>157.2899</td>
</tr>
<tr>
<td>7</td>
<td>626.0161</td>
<td>158.6059</td>
</tr>
<tr>
<td>8</td>
<td>255.2145</td>
<td>149.9586</td>
</tr>
<tr>
<td>9</td>
<td>-97.6088</td>
<td>118.7691</td>
</tr>
<tr>
<td>10</td>
<td>-749.8022</td>
<td>40.197</td>
</tr>
<tr>
<td>11</td>
<td>-997.985</td>
<td>0</td>
</tr>
</tbody>
</table>
Excel spread sheet to calculate column:

This part shows the Excel spread sheet used to verify the designed concrete columns.

Figure B-4 Structural design: Excel spread sheet for a perimeter columns level 1-3 (reinforcement)
Figure B-5 Structural design: Excel spread sheet for a perimeter column level 1-3
(interaction diagram)
Appendix C: Hourly air room temperature distributions

This appendix provides the hourly simulated indoor air temperature for the top floor of the building plotted against the hourly outdoor temperature to compare the inside thermal performance between different types of constructions. Section 6.4.3 discusses the hourly air temperature for two selected buildings in climate zone 2 (Brisbane). The data associated with the other climate zones is provided in the following figures (Figures C-1 to C-4).
Figure C-1 hourly air room temperature plotted against the hourly outdoor temperate for the Waffle.low and 200.normal in the climate zone 1 (Darwin).
Figure C-2 hourly air room temperature plotted against the hourly outdoor temperate for the Waffle.low and 200.normal in the climate zone 5 (Sydney).
Figure C-3 hourly air room temperature plotted against the hourly outdoor temperate for the Waffle.low and 200.normal in the climate zone 6 (Melbourne).
**Figure C-4** hourly air room temperature plotted against the hourly outdoor temperate for the Waffle.low and 200.normal in the climate zone 7 (Canberra).
Appendix D: Free-floating analysis during the design weeks

This appendix provides the data associated with variations of the indoor and outdoor air temperature for the designed buildings. Section 6.4.4 shows the results for two climate zones (1 and 6) during the winter design week. The free-floating analysis for the summer and winter design weeks associated with other climate zones is provided in the following section (Figures D-1 to D-8).

Figure D-1 Summer design week free-floating analysis for climate zones 1 (Darwin)

Figure D-2 Summer design week free-floating analysis for climate zones 2 (Brisbane)
Figure D-3 Winter design week free-floating analysis for climate zones 2 (Brisbane)

Figure D-4 Summer design week free-floating analysis for climate zones 5 (Sydney)

Figure D-5 Winter design week free-floating analysis for climate zones 5 (Sydney)
Figure D-6 Summer design week free-floating analysis for climate zones 6 (Melbourne)

Figure D-7 Summer design week free-floating analysis for climate zones 7 (Canberra)

Figure D-8 Winter design week free-floating analysis for climate zones 7 (Canberra)
Appendix E: Discomfort degree hours during the design weeks

This appendix provides the discomfort degree hours for two types of construction and structural materials (Normal and Ultra-lightweight concrete). Section 6.4.4 discusses the discomfort degree hours for summer conditions in climates 1 and 6. The analysis of discomfort degree hours associated with summer and winter conditions across the other climate zones is provided in the following section (Figure E-1 to E-8)

**Figure E-1** discomfort degree hours during winter design week for climate zones 1 (Darwin)

**Figure E-2** discomfort degree hours during summer design week for climate zones 2 (Brisbane)
Figure E-3 discomfort degree hours during winter design week for climate zones 2 (Brisbane)

Figure E-4 discomfort degree hours during summer design week for climate zones 5 (Sydney)

Figure E-5 discomfort degree hours during winter design week for climate zones 5 (Sydney)
Figure E-6 discomfort degree hours during winter design week for climate zones 6 (Melbourne)

Figure E-7 discomfort degree hours during summer design week for climate zones 7 (Canberra)

Figure E-8 discomfort degree hours during winter design week for climate zones 7 (Canberra)
Appendix F: Life cycle CO2-e emissions for the analysed buildings

This appendix provides whole lifetime CO2-e emissions normalised by gross floor area and separated by the type of concrete and method of construction. The figures associated with Darwin and Canberra were used in section 7.4 to compare the total CO2-e emissions associated with different forms of construction and types of concrete. The following figures (F-1 to F-6) provide the results for each city.

**Melbourne**

![CO2-e emissions graph for Melbourne](image)

*Victoria average state CO2-e emissions (kg/m²) intensity: 15,872

**Figure F-1 Life cycle CO2-e emissions normalised by gross floor area and separated by type of concrete and construction method- Melbourne**
Canberra

* ACT average state CO$_2$-e emissions (kg/m$^2$) intensity: 12,140

Figure F-2 Life cycle CO$_2$-e emissions normalised by gross floor area and separated by type of concrete and construction method- Canberra

Sydney

* NSW average state CO$_2$-e emissions (kg/m$^2$) intensity: 12,113

Figure F-3 Life cycle CO$_2$-e emissions normalised by gross floor area and separated by type of concrete and construction method- Sydney
Figure F-4 Life cycle CO₂-e emissions normalised by gross floor area and separated by type of concrete and construction method- Brisbane

Figure F-5 Life cycle CO₂-e emissions normalised by gross floor area and separated by type of concrete and construction method- Darwin