The increase of timber use in residential construction in Australia: Towards a sustainable residential development model

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A thesis submitted in fulfillment of the requirement for the degree of Doctor of Philosophy

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Certificate of authorship/originality

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

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List of peer reviewed publications during candidature

'Sustainable timber use in Australian residential construction: Perception versus reality'
Energy and Sustainability Conference
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'Sustainable timber use in the Australian housing market: Are consumers willing to pay the price'.
International Journal for Housing Science
Vol 37, No 3, 2013

'Medium rise structural timber apartments: Luxury or long-term carbon storage solution?'
SB13 Graz-Sustainable building conference
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'Multi-storey residential timber buildings in Australia: Where is the education?'
AUBEA
July 2012
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Abstract

There is currently a limited use of timber products in residential development in Australia due to the dominance of heavy materials such as concrete, steel and brick. This dominant use of heavy materials is a reversal of the traditional material choice that was based predominantly on timber products. Technological advances and efficiencies drove the change to heavy materials in these particular industries. The emerging issue with this reliance on heavy materials is the impact of their use on the environment. The carbon impact and problem of finite resource depletion associated with concrete, steel and bricks need to be addressed due to the increasing pressure from national and international requirements and legislation. The construction industry needs to reduce its negative impact on the environment and sustainable timber presents a material solution to the problem. Timber from sustainably managed forests and plantations can be utilised as lumber or manufactured into engineered products for residential development use in both detached and multi-residential projects. Whilst there is research on carbon reduction through timber use in residential construction there is a gap in the research into how timber can achieve adequate performance in the key indicators in the Australian construction industry. These indicators are cost, time, quality and sustainability. There is also historic prejudice and misperception toward timber use in construction from both the supply and demand side of residential development. This study aims to discover the current perception towards timber in residential development and produce a sustainable timber use model that addresses the key performance indicators of the Australian construction sector. The performance of timber when compared to the current heavy material use in residential development will be compared through the use of the model.

A survey was conducted to gauge the perception of the demand side of residential development of the current use of timber in the structural envelope and cladding of housing projects. Interviews were then undertaken with construction practitioners to gain a supply perspective of some of the issues with timber use from a technical perspective and to review if survey results were based on real timber performance problems or misperceptions. The data collected from the survey and interviews in addition to current literature on timber use in construction was used to develop a sustainable timber strategic building model. This strategic model provides an alternative model to the current heavy material use in residential construction. The model is tested and the results validated through ten building case studies by comparing the key performance factors when timber is substituted for non-renewable construction materials. When timber is used in the sustainable residential development model it is found to out perform traditional materials in aspects of time, cost, quality and sustainability.

Chapter 1 Introduction

This thesis studies how the use of timber impacts on the time, cost, thermal and environmental sustainability performance in residential development projects. Previous research has recognised the potential for both sawn and engineered timber to reduce the impact of buildings on natural resources and carbon production compared to heavy materials such as concrete, steel and bricks. However, most of the research fails to combine reduced environmental impact with key performance indicators such as cost, time and thermal performance. This thesis considers these other factors to produce a sustainable residential development model that competes and outperforms the current model that incorporates the use of heavy materials. The study draws on concepts of sustainability with a specific focus on the key performance criteria developed for the management of construction projects.

1.1 Background

Timber has been used in single dwelling and multi-residential construction for many centuries throughout the world depending on the available resources, technologies and skilled artisans (Kolb 2008). Australian buildings have incorporated timber in a variety of forms since British settlement drawing on the existing plentiful supply of local timbers (Cox, Freeland & Stacey 1980). The last three to four decades have seen an increase in the use of reinforced concrete floors and brick external walls in single dwellings at the expense of timber structural floor and external wall cladding (University of Tasmania 2008; URS Corporation Australia 2010). Materials used in low rise residential have shifted from timber structural and decorative envelopes to mainly reinforced concrete and masonry structural systems. This has occurred due to the increased cost efficiencies and familiarity with concrete construction and durability/fire concerns with timber. Steel and reinforced concrete have been the exclusive structural material systems in medium and high-rise residential buildings until recent innovative timber construction methods emerged.

Current usage of materials for structural components of housing and multi-unit developments has been estimated by the construction industry and demonstrates the dominance of heavy materials. Between 85-90% of new homes are built with external brick walls and concrete flooring (Kelly 2011). In multi-residential housing the wall and floor systems were estimated to make up approximately $550 million in revenue (2011/12 year), mainly made up of steel, concrete and glass (Kelly 2011). The continued domination of heavy building materials that require large quantities of production energy is under question due to growing social and legislative requirements to reduce the carbon emissions produced by the construction industry. Heavy materials is defined for the purpose of this research as those that are physically heavy per volume and/or take a lot of production energy to convert from a resource to useable construction product. The main heavy materials referred to in this research are steel and metal products, concrete, masonry products and glazing.

Australia has publicised commitments to reduce dramatically its year 2000 carbon emissions by 2050 and the State of New South Wales plans to reduce its carbon impact by 60% over the next 40 years (Australian Government 2012; NSW Department of Planning 2011). The majority of strategies employed by governments focus on reducing buildings' operating energy use (Monahan and Powell 2011). As these measures take effect there will be a greater need to reduce the production energy in the materials of construction (Mwashi, Williams & Iwaro 2011). Timber and engineered timber products offer part of the solution to reducing production and life cycle energy due to timber being considered a low embodied energy product compared to current building materials (John et al. 2011; Perez 2008). Whilst government legislation and client expectation are driving an increase in the environmental sustainability of new buildings, material choice is still predominantly based on cost, time and quality factors which up until recently have led to the choice of heavy materials (John et al. 2009; Holmes 2013). Another consideration regarding material choice is the perception of clients, construction practitioners and home consumers towards the characteristics of timber.

1.2 Problem definition

The increasing obligations on the construction industry to reduce its contribution to environmental damage come from both legislative mechanisms and public expectations. Additional incentives for material producers and builders to improve their environmental image comes from the marketing opportunities that provide access to 'green' money. The major material suppliers are all working to reduce the carbon emissions produced during the manufacture of their products (Flower and Sanjayan 2007: Norgate, Jahanshahi &Rankin 2007). The concrete industry promotes a higher content of fly ash in concrete to reduce the proportion of cement along with concrete's ability to absorb carbon during its life span. The steel industry bases its green credentials on the ability to reuse and recycle. Masonry suppliers market 'green' lines of blocks and pavers which have reduced cement content, use waste products from other material producers or reduce the amount of energy in their manufacturing process. The timber industry claims that timber can absorb and store more carbon during a tree's growth than is required during manufacture if it is burned for biofuel at the end of its life cycle as an alternative to fossil fuels (Gustavsson & Sathre 2006).

The many claims by material manufacturers and building companies of having the most ideal product have in the past been compared with their own previous goods or unfairly compared with competitor's commodities. A life cycle analysis (LCA) is often used to give a standardised value to the environmental impact of a product/system and allows for fair comparisons. The International Organisation of Standardisation (ISO) has provided the principles and framework for conducting analysis in the standard ISO 2006 (ISO 14044, ISO 14040). The international construction industry commonly uses life cycle analysis to compare between the environmental impact of different materials and construction systems. The following case studies are some examples of work conducted to date:

- Evaluation of the energy and environmental values for common building materials in order to produce guidelines for material choices (Bribian, Capilla & Uson 2011)
- Analysis of the proportion of an individual material's embodied energy in a semi-detached home in Scotland (Asif, Muneer & Kelley 2007)
- Comparison of the embodied energy values of dwellings that were predominantly constructed of wood, steel and concrete in the USA (Glover, White & Langrish 2002)
- Comparison of lightweight, concrete and super insulated houses in New Zealand on both life cycle energy and cost basis (Mithraratne & Vale 2004)
- Study of the energy content differences between building components (Kellenberger & Althaus 2009)
- Research into the importance of embodied energy in life cycle phases through their low energy case study of Italian residences (Blengini & Di arlo 2010)
- Discussion on the use of wood biomass to offset embodied energy in an eight-storey apartment building (Gustavsson & Joelsson 2010)
- Study of the carbon balances of five houses built in concrete or wood considering life cycle costs and carbon capture and storage technologies (Nassen et al. 2012)

There is also recent research by Carre in 2011 comparing different materials used for a typical house design on the east coast of Australia (Carre 2011). Despite all this research there seems to be a gap in the literature comparing timber against heavy materials in Australia based on thermal performance, life cycle energy (LCE), life cycle costs (LCC) and construction time aspects.

1.3 The current residential development procurement model

Life cycle thinking can be found incorporated into isolated building projects and building materials in Australia through LCA, however the construction industry in Australia is set up to deal with buildings by a linear process. Residential developments are designed and funded by a client that may or may not occupy the building and upfront considerations of the project will focus on return on investment or potential rental return and speed of construction. Project initiators rarely consider the end of life scenario or the destination of the materials in the building after demolition. Building companies are also driven by the need for profit and they often recommend to clients or select the quickest technique, material or method to achieve a low risk, high speed construction process. This provides challenges for the construction industry to change towards a circular model of construction processes that considers the types of materials at the beginning of the project that will reduce resource use and increase recycling opportunities at the demolition stage. A circular model would require not only upfront decisions about sustainable material use and design considerations but also consider speed of construction, cost of construction and maintenance and quality of the development. It would also require innovation from an industry that is reluctant to change and slow to embrace innovation (Holmes 2013). The incorporation of timber use in a circular residential development model has the potential to meet the sustainability objectives of the Australian construction industry in addition to the current performance criteria of projects (time, cost & quality). The idea of circular thinking in construction is defined in this research as considering the sustainable use of materials from their natural place of origin until its final use in future projects/as fuel or as landfill.

1.4 Motivation for undertaking this research

I am interested in the concept of sustainable construction and the opportunity to see buildings erected in such a way as to minimise waste at construction and demolition and for material reuse to benefit future projects. I also have an interest in seeing innovation and efficiencies introduced into our industry in order to save time and reduce costs without compromising on quality. Having travelled to countries in Europe in the course of my research I have witnessed technological advancements in construction particularly through the use of prefabricated timber elements, namely, thermally efficient construction and low energy buildings both from embodied and operating perspectives. Timber has also been shown to be simple to handle, durable and fire resistant when designed for installation in buildings according to its technical properties. It presents opportunities for increased safety and reduced costs related to site operations and construction speed. Other advantages that timber offers over heavy materials include carbon sequestration and storage, it is a renewable resource and requires simple machinery and processes to adjust during installation. This research was undertaken to identify barriers to both the supply and demand side of construction that prevent the increase of timber use and to develop a circular residential development model that promotes sustainability during construction, maintenance and the end of the building's life.

1.5 Research Aims and Objectives

The previous discussion identifies a problem that hasn't be addressed to date in literature. Timber structural envelopes have the potential to provide efficiencies in residential construction processes and reduce environmental impacts by decreases in the energy needed to construct, maintain and demolish residential developments compared to current methods and material uses. Additional research is required beyond the current state on timber use in construction. Understanding the barriers to an increase in timber use is key to providing a solution to the limited use of environmentally sustainable building materials and reducing the use of finite resources. Therefore, the initial aim of the research is to investigate whether the attributes of timber use in the envelope of residential construction provide performance issues compared to conventional materials such as brick and concrete in regard to sustainability, cost and time factors. It will also attempt to examine some of the barriers to the low utilisation of timber in both the detached and multi-unit markets. An additional purpose of this research is to identify the effects of the perception of homeowners and construction project decision makers on the supply and demand of residential building designs. Once these aims have been achieved through identification of the barriers and issues with timber use in residential development a generic sustainable residential development (SRD) will be developed to increase sustainability in the residential building sector. Timber will be used to test the SRD model using cost, time, quality and life cycle energy as performance criteria.

The specific objectives of the research are:

- Examining the benefits and challenges of using timber as an alternative to competing materials such as concrete, steel and masonry
- Investigating homeowner perceptions of timber use in homes and units and the reasons for their particular material selection.
- Reviewing current uptake of timber innovations in the residential construction industry and the distribution of information about innovations to construction professionals through education and training in Australia
- Examining key barriers to timber use through legislation, building codes and standards
- Assessing the relationship between sustainability, time and cost aspects of timber construction
- Identifying the current residential construction process using heavy materials
- Developing a residential development model to aid decision-making regarding sustainable material selection
- Testing the effectiveness of the model on building case studies to examine how it can improve time, cost and quality and sustainability over the current linear residential development model using heavy materials

Testing the sustainable residential model will be based on a number of propositions. The initial propositions of the case studies in this study are that timber construction with the same thermal rating as heavy materials performs better in the time, cost and energy characteristics. The propositions can be described in the following terms.

If timber thermal performance = heavy material thermal performance
Then

1) Timber construction time < heavy material construction time
2) Timber life cycle cost < heavy material life cycle cost
3) Timber life cycle energy < heavy material life cycle energy

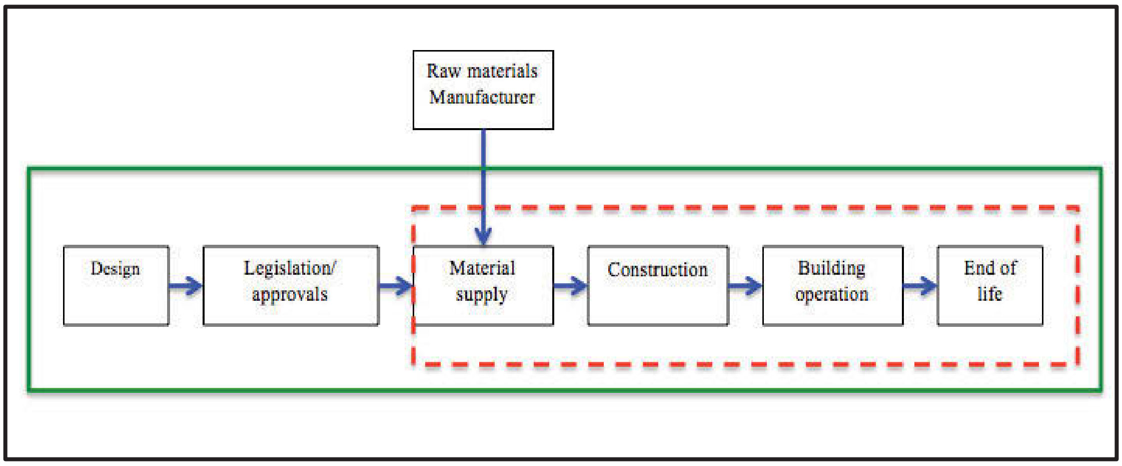
The case studies will include the redesign of typical residential brick and concrete homes into a timber structure alternative with equivalent envelope thermal performance to allow the propositions to be tested.

1.6 Research Scope and Focus

This research focuses on the use of timber in residential construction and in particular in the building envelope. The predominant use of timber currently in Australian construction is based on lightweight internal brick veneer applications in homes and architectural features. The research has a particular focus on the Australian market although it references international cases for the sake of comparison and to demonstrate the opportunities for change in our construction industry. The European market is established in terms of timber structural use in large residential and non-residential projects through prefabricated wall, floor and roof elements.

The residential construction procurement process is formed through a series of complex relationships between design professionals, project managers, trades people and material suppliers subject to legislative authorities, building codes and safety regulations. This complexity is a major reason why change in the industry is slow and business innovation in all but the largest construction firms is minimal or non-existent. This research investigates barriers to increasing timber use caused by the complexities of this system through a literature review, survey and interview data collection. It includes the majority of the players involved in this procurement system and manufacturing processes. The boundary for the literature review and initial data collection is shown in Figure 1.1 by the green solid line. In testing the proposed residential model through the use of case studies, the scope boundary is limited to the life cycle of the residential buildings shown in Figure 1.1 as the red dashed line. It excludes the design and approvals process. The reason for limiting the case studies to the construction, maintenance and end of life stage of the process is to eliminate countless variables related to individual council rules and costs.

Figure 1.1 Scope of research investigation and case study analysis



1.7 Research Method

The research will use quantitative and qualitative research techniques to establish the current perception of timber from both the supply and demand side of housing. The first part of the data collection will include a web-based questionnaire survey of homeowners and semi-structured interviews with construction professionals. The second part of the data collection will use ten case studies of residential dwellings in NSW to investigate sustainability, economics and time in comparing timber to conventional building materials.

The web-based questionnaire survey will be used to compile information about the perception of homeowners towards sustainable building materials, timber performance and material preference in new home building. This survey will target families that live in their own home in suburbs close to the city and in regional areas of NSW. Semi-structured interviews with construction professionals will help to reveal the concerns, capacities, challenges and opportunities related to the use of structural timber systems in medium- to high-rise residential projects in Australia. The literature review will guide the data collection aims of the survey and interviews. The data collected and analysed from this section will be used to present the current linear residential development model based on heavy materials. The results will also provide a basis for the formation of a sustainable residential building model using timber.

The case studies will be used to test the sustainable residential development model. Case projects will utilise ten recently constructed brick veneer homes redesigned with timber structural floor, timber flooring, timber roof framing and cladding homes with equivalent thermal resistance. Thermal modelling will be carried out using the computer program AccuRate to assist in the redesigning. A comparative Life cycle energy (LCE) and Life cycle costing (LCC) will then be performed on the original and redesigned dwellings. Time will also be considered to allow for the constraints faced in the residential construction industry. The data collected and analysed will be used to develop a decision model to aid design consultants/developers to identify the potential benefits of timber construction for residential construction. LCE is the energy taken to convert resources into materials fixed in place in a building and then removing it at the end of its life to its final place as recycled/reused or disposed. LCE includes transport, plant and machinery and human labour.

1.8 Outline of thesis

The structure of the study is as follows:

Introduction

Chapter 1 looks into the background and research problem for this thesis. Although previous research has recognised the benefit of timber for its sustainable attributes when compared to heavy materials such as concrete, brick and steel, less is known about how timber performs in terms of cost, time and quality. The current perception of timber proves to be a barrier to the use of timber systems and requires investigation to identify appropriate solutions.

Literature review

Chapter 2 reviews the literature on the concept of sustainability and its practical application to the Australian construction industry and on homeowner perceptions of housing and housing choice. It also investigates construction project performance and the integration of sustainability into project performance. This chapter concludes with a discussion on business models, business strategy, and business model innovations related to the construction industry.

Chapter 3 examines the literature on the history of timber use in construction in addition to current applications of timber and engineered timber products in residential projects both locally and internationally. The barriers to increased timber use are reviewed and the misperceptions surrounding timber use are compared to the actual performance of timber as reported in recent research. A discussion of how legislation and environmental assessment tools affect the use of timber in Australia concludes the overview of challenges to increasing the use of sustainable timber in residential development.

Chapter 4 delves deeper into the main performance indicators of construction projects that include time, life cycle cost (LCC), life cycle energy (LCE), and quality. Case studies using some of these performance indicators are discussed to establish how far investigations in this field of research have progressed. In this study the review discusses the foundation for LCA studies and some of the different types of LCA methods. However life cycle energy (LCE) is assessed in the testing of the case studies. This means that the focus is on energy used rather than the use of water, land, photochemical oxidation etc.

Research method

Chapter 5 covers the methodology chosen to meet the research goals. The research methodology used in this thesis combines qualitative and quantitative investigations. This chapter outlines the selection and application of the case study methodology and why it is the most applicable to this research. This chapter addresses the various forms of data collection and data analysis methods.

Data collection

Chapter 6 presents the results from part one of the research. Questionnaire surveys and semi-structured interviews are used to identify key issues and barriers affecting the increased uptake of timber in residential development. Surveys targeted homeowners both with and without a construction profession background and interviews were conducted with construction practitioners with a variety of experience managing project performance indicators such as cost, project management, contract administration and client side developments.

Data analysis and model development

Chapter 7 looks at the application of inductive reasoning is used to develop an understanding of the current residential development process using traditional materials. The literature review, survey and interview results support the establishment of the current residential development model and also provide a basis for a sustainable residential development model.

Model testing – building case studies

Chapter 8 presents the findings from ten building case studies in Australia. These case studies were used to test the new residential development model using timber in lieu of traditional heavy materials.

Conclusion and recommendations for future research

Chapter 9 provides an overall summary and conclusion which covers a number of key areas, including a brief summary of the research, a review of its aims and objectives, and any limitations and, finally, recommendations for further research.

Chapter 2 Sustainability, Decision theory and Business Model Innovation

2.1 Introduction

This chapter provides the background on sustainability theory and its application to the built environment and in particular to the residential housing sector of Australia. It will also look at how this affects the choice of material used in residential construction. The choice of materials for building homes, however, is not purely dictated by society or individual perspectives on sustainability but intertwined with supply and demand forces on home purchasers and homebuilders. For this reason this chapter will also discuss consumer choice theory and its application to home purchasing and will identify the major performance motivators for suppliers to construction projects of which time and cost are regarded as the most important. The final section of the chapter will investigate business strategy and business models and look at the relevance to residential construction companies of the theory of business model innovation in incumbent firms.

2.2 Sustainability theory – background

The theory and concepts of ecologically sustainable development (ESD) are under continuous interpretation and so there is an absence of a detailed theoretical framework (Jabareen 2004). This has led to ESD policies being developed in a subjective fashion to suit nations, industries and societal constructs depending on particular industry needs, and the political, economic and social circumstances of the day (Andrews 1997). Sustainability theory can therefore be described as a contested concept suitably falling under Gallie's description of essentially contested concepts (Lafferty 1996: Jacobs 1999):

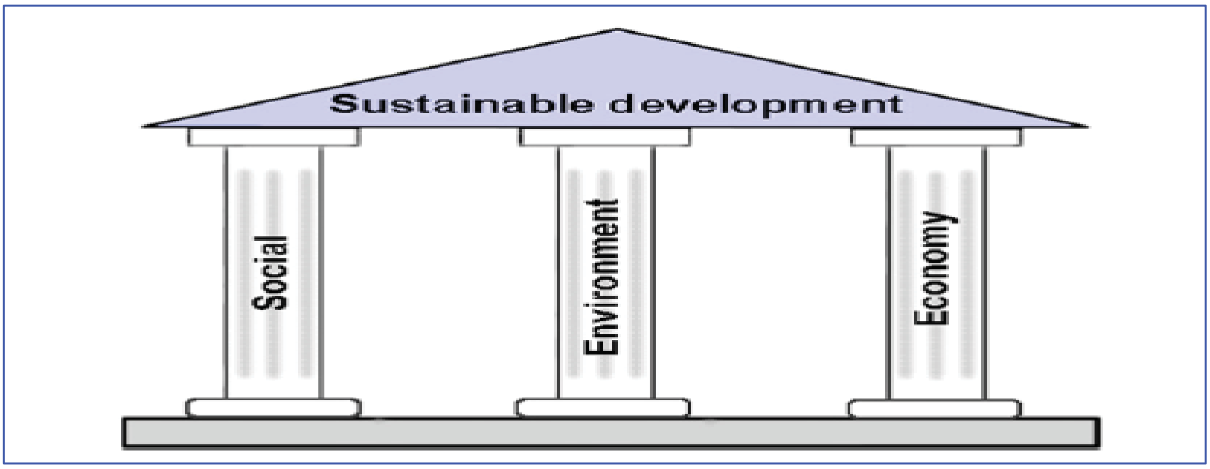
> Any particular use of any concept of common sense or of the natural sciences is liable to be contested for reasons better or worse; but whatever the strength of

> the reasons they usually carry with them an assumption of agreement, as to the kind of use that is appropriate to the concept in question, between its user and anyone who contests his particular use of it (Gallie 1956, p. 1).

Despite the lack of understanding of the theory of ESD and varying descriptions of the concept based on individual fields, many journal authors cite the definition of ESD from the Brundtland Report (1987, p. 15), namely, "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." This two-pillar model representing environment and development issues is defined in the literature as a triple bottom line model that separates the development component into social and economic issues to provide the three pillars (Pope, Annandale & Angus 2004).

Despite the different categorisation of the three pillars of sustainability, they are linked to a number of more specific and sometimes competing issues such as poverty, equity, environmental quality, safety, and population management (Heijungs, Huppes & Guinee 2010). Whilst the relationship between the three pillars and their associated issues are often viewed as a series of tradeoffs, some researchers believe that an integrative approach to sustainability is preferable (Gibson 2008). Figure 2.1 pictures the concept of sustainable development being supported by the three aspects of sustainability. This is a popular representation of the requirement for all pillars to be equally developed to achieve sustainable development (Heijungs, Huppes & Guinee 2010).

Figure 2.1 The three pillars of sustainable development



Source: Heijungs, Huppes & Guinee 2010

Jaboreen (2008) discusses a more complex model that includes seven separate concepts of ESD and presents a theoretical framework for ESD described in Table 2.1.

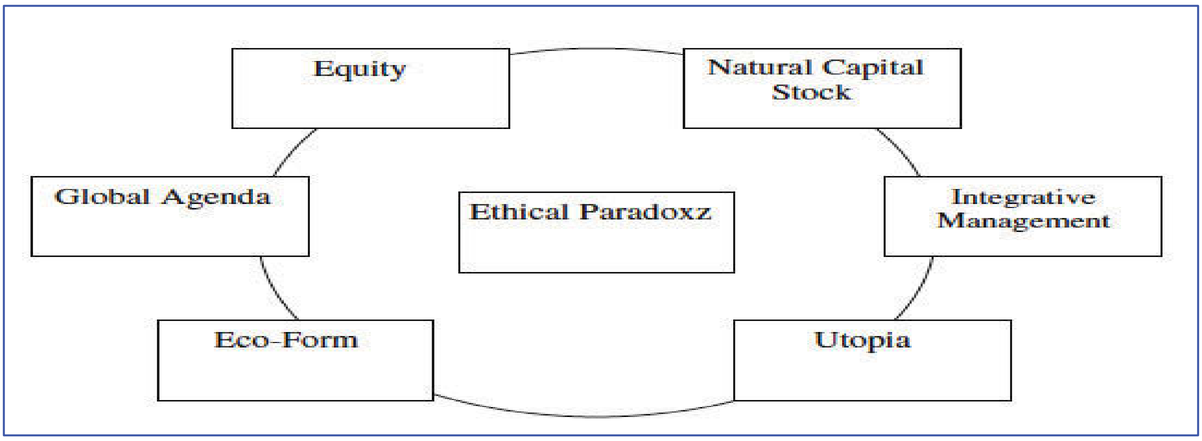
Table 2.1 Seven concepts of ESD

Concepts of sustainable development	
Ethical Paradox	**Sustainability**-process or state that can be maintained indefinitely. **Development**-environmental modification/exhausts natural resources
Natural capital stock	Stock of all environmental & natural resource assets Divided into 1) Non-renewable resources 2) Capacity to produce renewable resources 3) Capacity to absorb emissions and pollutants
Equity	Balance of social, environmental, economic justice, social equity, quality of life, freedom, democracy, participation and empowerment.
Eco-form	Ecological design contributes to the reduction of air pollution and increased energy efficiency
Integrative management	Integrative and holistic management of social, economic and environmental concerns
Utopianism	Utopian view of sustainable development is one where justice prevails; all are content and live in harmony with nature. Where there are no shortages or abuses
Political global agenda	SD seen as a challenge for global management. Focusing on poverty eradication, consumption and production patterns and managing resources for economic and social development rather than just ecological matters

Source: Adapted from Jaboreen 2008

These seven concepts of sustainable development have been assembled into a theoretical framework by Jaboreen (2008), placing the ethical paradox of sustainable development at the centre of the remaining six concepts. This is shown in Figure 2.2.

Figure 2.2 Conceptual framework for sustainable development



Source: Jabareen 2008

Whilst theoretical frameworks can communicate the concepts surrounding ESD and associated issues, implementing ESD solutions can be quite complex. The current challenge for governments is to apply policies and legislation that balance allocation, distribution and scale according to available natural and made stock (Daly 1992), that is, to ensure the following:

- The efficient use of resources amongst particular types of end product
- The equitable division of resources embodied in goods and services amongst the current population and future generations
- The volume of natural materials used in production and returning to the environment as waste

The additional challenges of looking after existing stocks, renewable resources and absorbing pollutants must all be managed within the restraints of a global sustainability framework. These must be addressed whilst governments attempt to meet the expectations of their constituents as elected governors of the people. Each nation will make decisions on ESD policies depending upon their international obligations, access to natural and made capital and their view of the concepts of sustainability. Vob (2005) discusses sustainability concepts based on substitutability. 'Weak sustainability' is that which relies on replacing natural resources with man-made capital whereas 'strong sustainability' is based on reducing activity that diminishes natural capacity rather than increasing economic activity. Wilkinson (2013) has broken down these two concepts into five graduated standpoints on sustainability. Very weak sustainability is known as anthropocentric; the other end of the scale is seen as ecocentric and this where the deep ecologists sit.

1. Very weak sustainability is labelled cornucopian environmentalism. This is resource exploitive, substitutive based, and believes in the right of humans and also the unfettered pursuit of capitalism
2. Weak sustainability, which is also known as accommodating environmentalism believes in equity across generations, managed growth, recycling and the conservation of resources
3. Strong sustainability is associated with moderate ecology and proponents accept the need for zero population increase and admit that capitalism is not sustainable. They are conservationist and reject consumerism
4. Very strong sustainability includes deep ecologists and transpersonal ecologists. Deep ecologists admit a maximum carrying capacity of the earth, condone a heavily regulated economy and encourage a reduction in population
5. Transpersonal ecologists have a religious level of belief, reject consumerism, lack faith in technology and believe in a population cull

Australia fits into the second category of weak sustainability (accommodating environmentalism) that is located toward the anthropocentric end of the sustainability standpoint and is the dominant worldview (Wilkinson 2013). Whilst Australia has implemented strategies to reduce water and energy consumption in different sectors over the last 20 years it has increased the impact of policies significantly in the last 2-3 years through the introduction of a carbon tax and a sharp rise in energy prices (Australian Government 2014; Parliament of Australia 2013). However, Australia recently repealed the carbon tax and is still heavily dependent upon coal, which provides 80% of the nation's electricity and produces more carbon emissions than any other type of electricity generation (Australian Government 2014). Australia has committed to reducing its 2000 emissions by 5% by the year 2020 through the global treaty known as the Kyoto Protocol (Australian Government 2012). The built environment contributes close to 50% of greenhouse emissions and, therefore, is an area of research that has received considerable attention (Wilkinson 2013). The following section looks at the Australian construction industry and the way it understands the concept of environmental sustainability and addresses ESD through policies and practices.

2.3 Sustainability and the Australian construction industry

The Australian construction sector causes approximately 23% of national carbon emissions (Centre for International Economics 2007). This sector has the capability of improving sustainability through improving operating energy efficiency and reducing embodied energy in buildings through material choice used in construction. The main focus for reducing the industry's environmental impact has been to reduce the operational energy in the use phase of a building's life cycle and this is common both locally and internationally (Monahan & Powell 2011; Gustavsson & Joelsson 2010).

Operational energy is the energy used for heating, ventilation and cooling, lighting, hot water, cooking and any other facilities to keep a building functioning for its intended purpose (Treloar et al. 2000). Many variances to the factors affect a building's operating energy such as the purpose of the building, occupation number, energy source, local climate, building materials type and quality, as well as air changes and occupants' habits (Ramesh, Prakash & Shukla 2010). There are also variations in defining operational energy with some studies including just heating, cooling and ventilation while other studies address heating, lighting, appliances, cooking and hot water. In most cases the latter definition is utilised (Ramesh, Prakash & Shukla 2010; Itard 2009; Sartori & Hestnes 2007; Treloar et al. 2000).

Over 30 years ago, operating energy made up 90 to 95% of a building's life cycle energy (Hallquist 1978; Hannon et al. 1998). A study by Treloar et al. in 2000 showed that the operating energy made up around 75% of the overall primary energy use (life cycle 75 years). This is similar to study results by Itard (2009) for a traditional Dutch dwelling that compared it with a reference building with low energy designs. The study reported the low energy design building's operational energy was between 56% and 69% due to the reduced operating energy consumption and increased embodied energy component (Itard 2009). Satori and Hestnes (2007) reviewed approximately 60 case studies including multi-residential and detached housing and found that the operating energy of low energy buildings was 70 to 75% of total energy. A more recent case study review found that self-sufficient homes could have zero operating energy by using complex technical installations. However, the life cycle energy was found to be greater than for low energy homes due to the large embodied energy proportion (Ramesh et al. 2010; Satori & Hestnes 2007). These case study examples show that operating energy is a reducing part of overall life cycle energy and the use of materials that make up the embodied energy component is now of more importance in material selection for building design.

Whilst the focus on reducing the construction industry's environmental impact has been on operating energy, there is a growing concern about minimising the embodied energy in homes and apartment buildings (Blengini & Di Carlo 2010; Mwashi, Williams & Iwaro 2011; ABCB 2012). Wooden structures have significantly less embodied energy and related carbon emissions than equivalent designed steel and concrete buildings. In addition they provide a carbon sink as a construction material (Schmidt & Griffin 2012). Timber is likely to increase in popularity due to it being considered a low embodied energy product compared to common residential building material alternatives (Fraisse et al. 2006). The displacement of CO_2 has been estimated for the use of timber in lieu of material alternatives as in the order of 3.9 tons per ton of timber (Sathre & O'Connor 2010). Estimates of carbon sequestration are around 1.0 ton per metre cubed of timber (Lehmann 2012). A number of case studies have compared the carbon impact of using timber against heavier materials such as concrete, bricks and steel for structural elements in both residential and non-residential buildings. Some of these are listed in table 2.2.

Table 2.2 Timber versus heavy material residential case studies

Main research themes	Results	Authors
CO_2 balance wood v concrete in multi-storey building	Embodied energy for concrete 60-80% > than timber	Borjesson & Gustavsson 2000
LCA case study of home materials-Scotland (Concrete, timber, aluminium, glass etc.)	Concrete has highest Embodied energy %	Asif et al. 2005
Compare embodied energy in homes (Mixed weight materials v heavyweight)	50% < Embodied enegy light construction	Mendoca & Braganca 2007
Primary energy -8 storey timber building case study	Negative Co2 balance for timber building due to sequestration	Gustavsson, Joelsson & Sathre 2010
LCA Australian case study. Timber v brick veneer/concrete floor	Timber outperforms brick veneer	Carre 2010
LCA brick v timber optimised design-Sydney	GHG savings with timber design	Ximenes & Grant 2012

The case studies in Table 2.2 demonstrate that timber buildings have been shown to have a carbon reduction benefit over those buildings using heavier materials. The increased use of timber in residential construction could provide not just environmental benefits through the reduction of carbon production, but could also reduce the weight of buildings as well as construction time and cost when compared to existing building methodologies. Current usage of materials for structural components in housing reveals the dominance of heavy materials such as concrete, brick and steel. Between 85-90% of new homes in Australia are built with external brick walls and concrete flooring (Kelly 2011). In multi-residential housing the wall and floor systems are estimated to be worth $550 million per year in revenue (2011/12 year), consisting primarily of steel, concrete and glass (Kelly 2011). Concrete flooring and brick external walls have replaced timber for residential structural and cladding in the last 30-40 years despite a long history of timber use in residential construction (URS 2010; University of Tasmania 2008; Cox, Freeland & Stacey 1980).

The reasons behind the supply and demand for particular types of housing, construction methodologies and material usage are investigated in the following two sections. Section 2.4 discusses the demand side of housing by looking at consumer choice theory and its application to housing choice and the demand for particular types of housing. Section 2.5 then looks at housing supply in terms of the key motivating factors for developers and builders to build with particular materials and construction methods and the incorporation of sustainability into this framework. Section 2.6 finishes this investigation by looking at current business strategies and models in the construction industry and challenges of innovating existing business models. The inclusion of environmentally sustainable practices, new construction technologies and materials into existing business models falls under the category of business model innovation.

2.4 Consumer choice theory

This section discusses the theories behind consumer behaviour and human decisions and applies them to the choices by consumers of houses. It reviews the traditional influences on home selection and the factors that guide these purchase decisions. The influence of environmental considerations in new home purchases and the choice of materials is also reviewed.

Homebuyers are generally considered personal consumers because they predominantly buy a home for their own use. The way these decisions are made fall under consumer choice/behavioural theories although it must noted that consumers as individuals may not act according to particular patterns (Schiffman, Kanuk & Wisenblit 2010). Normative theories are often used in the study of choice because they focus on the optimisation of the process that results in a person's final selection (Einhorn & Hogarth 1988). This process of attempting to improve behaviour, reduce errors and reduce the time required to make decisions as well as finding the best route to a choice is an engineering approach (Edwards 1977; Hammond, Mumpower & Smith 1977). Simon (1978) suggests that optimisation in decisions (rationalisation) should not be assessed purely from the economic perspective but be generalised to include the sensible and reasonable approach based on the assumption that choice behaviour is functional and leads to the achievement of goals. Human judgement and choice have been found to contain many errors and biases when compared to the optimisation process (Rachlin & Burkhard 1978; Staddorn & Motheral 1978). Measurement of optimisation usually involves having a set of criteria (e.g. profit, time, loss etc.) and most choice scenarios will not provide an optimal solution due to their multiple, often conflicting criteria (Shepard 1964). This results in compromises and trade-offs that reflect the values of the person making the choice (Einhorn & Burkhard 1978).

Fletcher (1999) suggests that people can make decisions in either a rational and scientific manner or a self-serving/biased way. This can depend on factors such as social context, personal motivations, memory and individuality (Fletcher 1995). It can also change between the type and size of purchase for the individual in that the same person may try to optimise their decision for a high cost item but be unthinking in a low value purchase. Simon (1982) focused on the process of making decisions rather than their outcomes and suggested that decision paths were based on 'rules of thumb' and that once the decision maker found a satisfactory solution based on a set of minimum criteria it was implemented rather than continuing the search for the optimal solution.

2.4.1 Economic behaviour

Alhadeff (1982) suggests consumer behaviour results in either positive or negative reinforcement and predicting purchase behaviour relies on understanding both this learned experience and the context or place of the consumer's behaviour (Foxall 1997). Where consumers lack experience in making a particular type of purchase, they behave according to other people's experiences (rules) and subjective norms until they have developed their own rules through experience (Foxall 1997). Whilst these rules can be produced from memory for use in similar circumstances, differing choice environments may elicit a spontaneous decision strategy, which emphasises a need to understand contextual influences (Bettman 1979).

Factors that also influence the strategies of a decision maker will be the desire to make the right decision while using limiting amount of cognitive effort (Payne et al. 1993). Strategies are selected in a trade-off between the likelihood of that strategy accurately producing a good decision versus the effort required implementing the strategy in that situation. The stresses and risks associated with the outcomes from decisions and the decision environment itself have been seen to produce emotions of anxiety and worry, which may lead to the use of more extensive and attribute based strategies (Luce et al. 1997). Bettman (1979) has demonstrated the importance of emotion in the decision making process which is not considered in the optimisation process of rationalisation.

People's judgements and decisions are usually based on a small set of facts or information that is available to them at the time of the decision regardless of whether they may be improperly applied or despite the additional information available but not within ready access (Wyer 2008). This is no different in consumer choices where decisions will be made with the criteria available at that point in time (Wyer 2008). If a comparison of two products is required, the characteristics of each may be analysed to evaluate the product with the greater number of superior attributes. However, if there is no clear winner or the evaluation requires too much effort, a decision may be made on the basis that one product is viewed by the majority as the most popular (Wyer

2008). If the consumer has previously made such a comparison they may make their choice based on these past preferences (Park & Kim 2005).

If there are knowledge gaps in the information held by a consumer about a particular product they may make predictions about the quality of a product based on the price. An expensive product may be presumed to be of good quality or, if it is made by a particular brand, then it will thought likely to be of similar quality to other goods produced by that brand (Kardes et al. 2004). This is often the case with brands of motor vehicles, wine and fashion labels.

2.4.2 Consumer behaviour

In understanding consumer behaviour it is necessary to distinguish between behaviours of consumers when there is a single option or multiple options, although in reality every choice comes down to the option of whether to buy or not to buy (Azjen 2008). Four behaviours make up the option to buy: 'what to buy', which 'brand to buy', the 'context of the purchase' (shop or online) and the time (Azjen 2008). The decision to purchase requires consumers to deal with a range of information such as options, new models, longevity of product, and serviceability of a product in addition to contemplating all the outcomes of the purchase both initially and long term (Albert, Aschenbrennar & Schmalhofer 1989; Peter & Olsen 1993; Slovic, Lichenstein & Fischer 1988). This information then needs to be analysed and a course of action decided upon and these are usually followed up by evaluation of the purchase and a source for future decisions (Azjen 2008). When assessing the different attributes for different models, the consumer is likened to a statistician in considering all the variables and placing different values on particular attributes prior to making a final judgement (Peterson & Beach 1967; Azjen 2008).

Social values are often the underlying driver of decision making involved in people's attempts to achieve their goals. These goals include the types of purchases made by individuals and families and their expectations of particular products (Kahle & Xie 2008). These types of decision-making drivers also apply to the motivations of house consumers towards particular housing designs that can represent status, cultural diversity, nostalgia and authenticity (Kahle & Xie 2008).

Goal pursuit also influences consumer choice and this varies according to whether the consumer has single or multiple goals. Single goal pursuit generally provides a higher opportunity for attainment over the consumer with multiple goals because each additional goal requires more product attributes and involves goal competition (Fischback & Dhar 2008). Applied to housing this can present a challenge due to the variety of characteristics in each home unless it is specifically designed for a particular individual or family. The single goal of a three-bedroom home can be more easily satisfied than the goal of a three-storey home near a train station which is made of brick with a pool in the back or front yard.

2.4.3 Summary of choice behaviour

In applying normative theories to the behaviour of consumers and choice situations, many issues apply to reduce the chance of the optimal decision. These include the following:

- Choice behaviour can be based on the achievement of individual goals rather than economic optimisation
- Bias and errors are often introduced in the optimisation process
- There are often multiple conflicting criteria in the choice process which leads to trade offs and compromise
- The number of available purchase options
- The challenge of weighting/prioritising attributes of a product that has multiple or numerous attributes
- Lack of information available to the consumer
- The value of the purchase can affect the choice process (e.g. high value items may get more consideration/investigation than low value goods)
- Personal or family values that will affect the choice process
- The education, choice memory and experience of the consumer

The issues listed not only reduce the chances of the optimum purchase for basic consumer goods but also for consumer durables such as houses.

2.4.4 Housing choice

The choice of houses introduces added complexities because of some of the additional attributes/decision factors that may not be found in simple consumer choice options. Some of these are listed below.

- Government regulations (Priemus 1984)
- Limited stock availability in particular areas/suburbs
- House location in addition to the attributes of the home (e.g. vicinity of work, leisure, transport, views) (Gibler & Nelson 2003)
- Proximity to schools
- Position of the home on a particular site (front, middle, back of the block, shading, privacy from neighbours)
- Slope of the site (vehicle access, cost of future building renovations/new house build)
- Proximity of home to family and friends
- Age of the home being purchased (future renovations/maintenance costs)
- Number and age of family members moving into the home (affecting the size of the house, outdoor areas, living areas and amenities)
- The current living circumstances of the purchaser (renting/owner occupied/moving from a different area, state or country) (Janson, Coolen & Geotgeluk 2011)
- Future income of the home consumer (Priemus 1984)

The challenge for consumers is to choose from the available housing attributes that will produce the consequences (benefits) that meet their values. In most circumstances there will be an overlap in the consumer's values that are activated by the choice object and situation (Coolen & Hoeksta 2001). Unlike many consumer products, houses are known more for their defining attributes than their brand names and most house choices will be defined by attributes such as height (one/two-storey), number of rooms, external wall material, block size, house age (renovated or out-dated), aspect, type of suburb, vicinity to transport and shops as well as price. In an attempt to predict the choices of consumers, researchers mentioned in the next section have conducted surveys, interviews and data searches in attempts to model the way in which people will select a home. Stated preferences for housing types and analysis of real choices are both briefly discussed below.

Stated preferences for housing as compared to the revealed preferences (actual choice in real markets) is based on hypothetical choices and the motivations are driven by the values and goals of the purchaser (Coolen & Hoekstra 2001; Timmermans, Molin & Noortwijk 1994). Choice behaviour is determined by the consumer's objectives which are derived from particular values and lead to the search for a particular existing home or design of a new home (Simon 1987). Functional choices based on goal-directed behaviour are not necessarily the optimal choice and this is often the case in housing choice (Beach 1990). Whilst the strength of revealed data is that it is based on observed behaviour, it does not provide the choice strategy, choice sets available at the time of purchase, or any unusual/uncommon housing attributes (Einhart 2002). The main criticism of stated preference is that the questions and choices are all hypothetical and don't require a financial commitment from the participant (Mitchell & Carson 1989). However, in a comparison study between revealed and stated housing choices by Einhart (2002), similar hypothetical choices of housing attribute sets were made by participants when compared to actual purchases in a particular real estate region.

Due to the lack of both multi-residential and detached homes presently being constructed with timber in Australia, an investigation of consumers perception of time, cost and environmentally performance of currently used building materials will be undertaken through consumer stated preferences. The first part of the investigation is found in Chapter 3 through the review of studies looking at surveys of the perception of consumers and construction professionals towards the use of timber in housing and their views regarding some of the benefits and barriers/disadvantages of timber in residential construction. The second part of the investigation is the analysis of data from a survey of Australian residents regarding their perception of ESD and sustainable building materials in new buildings, timber as a sustainable material for housing, and the thermal, time and cost performance of timber. The survey results will be compared to the information found in the literature to identify barriers to the increased uptake of timber in new housing.

Having investigated some of the motivations for consumers to choose their houses, the following section looks at the supply side of building and some of the reasons for builders and developers adopting particular construction methodologies in building projects. This includes the current performance drivers for construction projects and the increasing social and legislative pressure to incorporate environmental sustainability into construction projects.

2.5 Construction project performance indicators

Construction project success varies depending on the major stakeholders and there are multiple ways of measuring that success just as there are a large number of contributors to achieving it. The multiple contributing factors can be found in the areas of project management processes, type of project, external factors, procurement procedures and human related factors (Chan, Scott & Chan 2004). The focus of this discussion will be on the success factors or performance indicators of the outcome of a construction project, as viewed by the developer, builder and client (Toor & Ogunlana 2008). The discussion does not, however, look into success criteria related to the intended function or the satisfaction of the end user that has been investigated in some of the literature (Chan & Chan 2004). Various researchers have contributed to this discussion as can be seen in Table 2.3. The table displays the main indicators tied to project success since the early 1990’s and are well known to construction industry participants. These prominent project success indicators are time, cost and quality and they have been described as the iron triangle (Atkinson 1999).

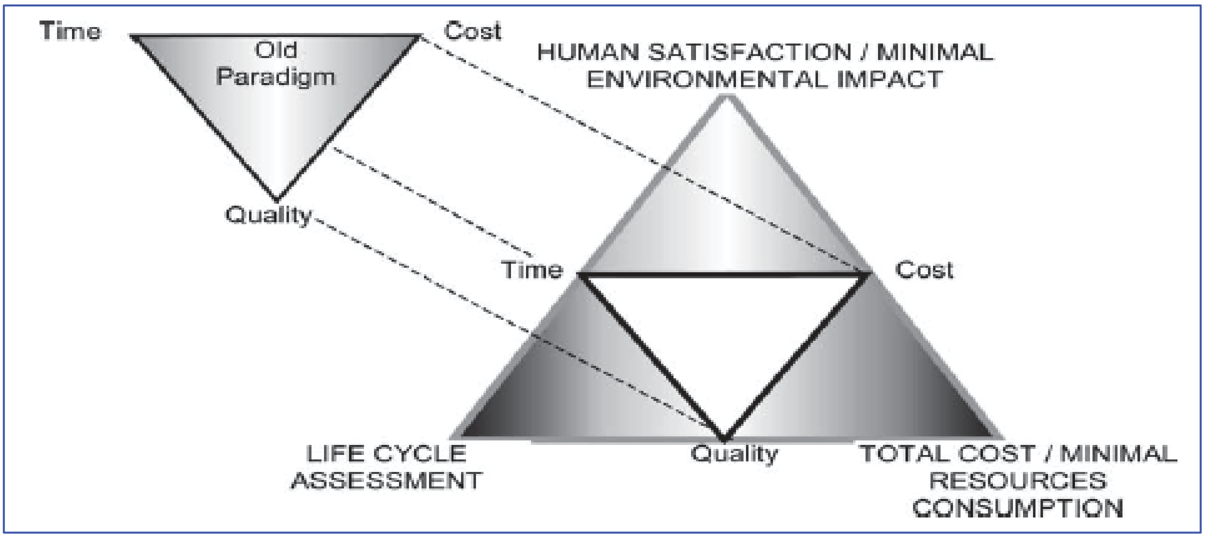
Table 2.3 Main success indicators/criteria of construction projects in 1990's

Topic of literature	Performance Indicators	Authors
Indicators of construction project success in the delivery stage	- Cost - Time - Quality - Efficiency	Atkinson (1999)
Micro viewpoint of project success (Construction only-not operation)	- Time - Cost - Quality - Performance - Safety	Lin & Mohamed (1999)
Contractor selection criteria affects upon the success factors of construction projects	- Time - Cost - Quality	Hatush & Skitmore (1997)
Critical success/failure criteria for projects	- Time - Cost - Quality - Client satisfaction	Belassi & Tukel (1996)
Project management systems	- Time - Cost - Quality	Navarre & Schaan (1990)

In the last 10-15 years other indicators in addition to time, cost and quality have been discussed as important factors when considering the success of construction projects. Two increasingly common indicators are worker health and safety and environmental performance (Beatham et al. 2004; Chan & Chan 2004; Crawford & Pollack 2004; Abu Bakar et al. 2010; Han et al. 2012).

In Australia strict legislation ensures minimum safety requirements and significant penalties and jail terms can apply if regulations are not implemented on construction projects. For this reason construction safety is not discussed as part of this review. The other four project success indicators (time, cost, quality and sustainability) are largely determined through specific project contractual arrangements although, as mentioned above, there is a movement towards greater regulation of building project environmental sustainability factors. The previous iron triangle of time, cost and quality mentioned in Atkinson (1999) has been updated to express the sustainability dimension in Figure 2.3 to represent the new paradigm for sustainable construction.

Figure 2.3 The new paradigm for sustainable construction



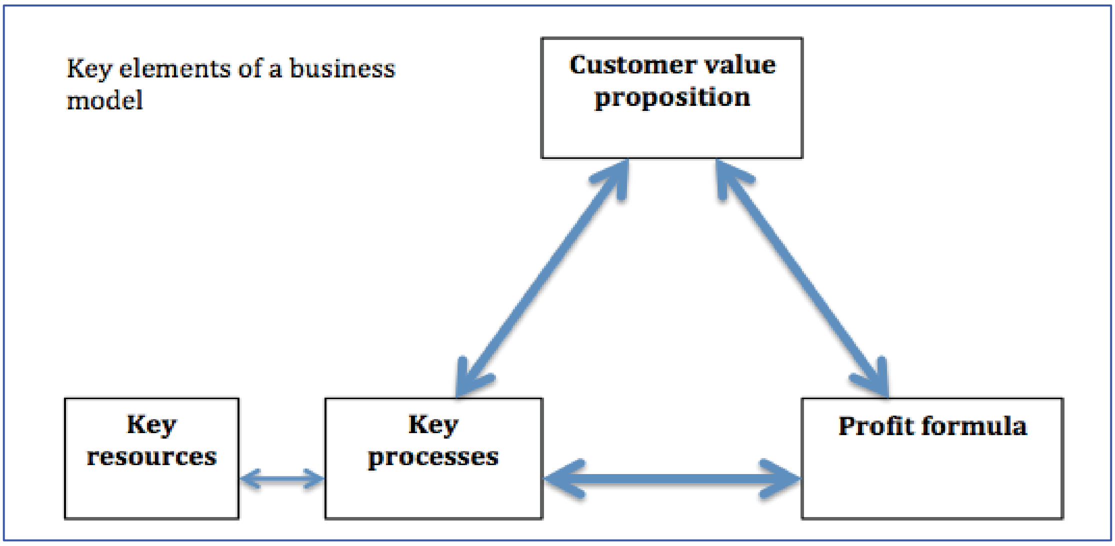
Source: Gilchrist & Allouche 2004 (modified Vengas et al. 1996)

The future of construction in Australia is going to be increasingly influenced by environmental sustainability as the government aims to reduce year 2000 carbon emission levels by 80% by year 2050 (Australian Government 2013). This will require construction businesses to adjust their business strategies to incorporate sustainability to be able to continue to achieve their existing major project success criteria. The literature indicates that timber use in residential construction is an effective way to reduce carbon emissions in construction projects and a few larger Australian developers now promote ESD as part of their marketing strategy (Stocklands 2013; Mirvac 2014; Lendlease 2013; Sekisui House 2014). Smaller businesses don't have access to resources to change strategies and business models as quickly or efficiently as large firms, although they will be required to adjust their business models to accommodate sustainability alongside carbon reduction legislation (Galharret & Wang 2011). The following section reviews the literature on business models and strategy, the current understanding of business models in the construction sector and the theory of business model innovation in incumbent firms and its application to the construction industry.

2.6 Business models and strategy

The term 'business model' varies in the literature and includes simple definitions such as the way a business generates income from its activities to more complex ideas of managerial processes for the design and analysis of the company's value creation (Galharret & Wang 2011; Pekuri et al. 2013). According to some authors, its purpose is to differentiate and give advantage to a company over its competitors and others describe it as the playmaker of a business (Johnson et al. 2008; Teece 2010; Carroll 2012). Da Silva and Trkman (2013) suggest that business models are the combination of the business resources that create value for customers and the business by way of transactions. Value can include price, speed, design, experience, performance, status, useability and accessibility. The clearer a business model is in how it creates and delivers value for both the business and customer, the more effective it is in pursuing growth (Johnson 2010). Figure 2.4 represents a customer value proposition model.

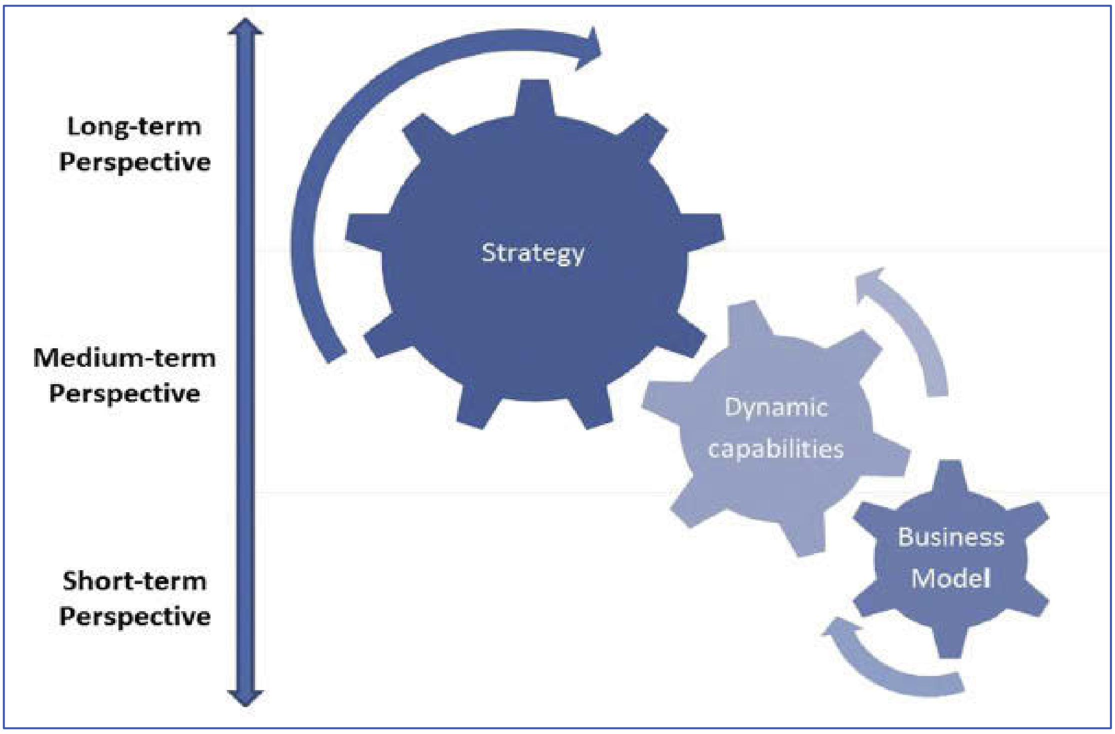
Figure 2.4 Customer value proposition model



Source: Osterwalder & Pigneur 2010

Whilst there seems to be confusion between the terms business model and strategy it is argued that a business model is what a business is at a given time and strategy represents what the business wants to become (Da Silva & Trkman 2013; Casadesus-Masanell & Ricart 2010). Some authors argue that all businesses have a business model but not all have a strategy and some businesses or their customers do not even have an understanding of their model but carry out their work practices in the hope of a decent financial return (Carroll 2012; Casadesus-Masanell & Ricart 2010). Business strategy is seen as important in assisting businesses to cope with the complexity of current business environments, rapidly changing client needs, taking advantage of weaknesses of competitors and planning for unexpected change (Grant et al. 2011). Da Silva and Trkman's (2013) strategic framework suggests that business strategy shapes dynamic capacity development that can then alter the business model. The dynamic capabilities of a business include human resources, tangible assets, capacity to change and adjust to the market and other circumstances to gain competitive advantage (Pavlou & El Sawy 2011; Teece 2009). Figure 2.5 shows the framework produced by Da Silva and Trkman (2013).

Figure 2.5 Business strategy framework



Source: Da Silva & Trkman 2013

2.6.1 Business model innovation

New technology and innovation adoption by organisations, along with advances in communications and information technologies, have enabled companies to create new ways to deliver value and exchange goods and services (Timmers 1999; Amit & Zott

2001). This has driven the surge in interest in business models since the mid to late 1990's and the opportunity to design new business models to take advantage of new technologies (Mendelson 2000; Comes & Berniker 2008). Business model innovation (BMI) has been linked to success whether in the area of supply chain, value generation or value chain positioning and those firms that emphasise innovation financially outperform businesses that don't readily implement change (Giesen et al. 2007). Innovation adoption and change in business models are crucial for companies to thrive in a time when technology advances are so rapid (Hamel 2000; Zott, Amit & Massa 2010). Some additional drivers for business model innovation come from regulatory or legal changes, globalisation, mergers and acquisitions, and new market opportunities (Comes & Berniker 2008). Customer power has also increased with the availability of free information and easy comparisons so businesses need to be more customer focused, and continually re-evaluate their value propositions to customers so as to stay adaptive in changing markets and maintain viability (Teece 2010). McGrath (2010) recommends that business model change should focus on creating value for customers in order to create value for the business. Additional concept considerations for business model innovation include experimentation, temporary competitive advantage rather than sustained competitive advantage, and the evolving business model (McGrath 2010).

2.6.2 Business model innovation in incumbent firms

Existing firms implementing business model innovations can benefit from lean value creations by not having to wear all the costs of innovation present in start up companies and need only endure organisational change (Santos, Spector & Van der Heyden 2009). An initial barrier to BMI for incumbent firms is an understanding of their own current business model (Johnson et al. 2008). Another barrier is the potential for the firm to compete against one of its existing products or to unsettle existing supply chains or customers, depending on whether the business model change relates to new products, quality or supply (Teece 2010). If the BMI requires exploiting a disruptive technology it may conflict with the existing business model of the incumbent firm and its managers will be reluctant to encourage any innovation that may threaten their value to the company (Christenson 1997; Christenson & Raynor 2003; Chesborough

2010). Once the concerns of a new model have been worked through, the next challenge for existing companies is to experiment with the new model using real products and customers to obtain speedy feedback at the lowest price to enable quick evaluation of the new model (Thomke 2002; Chesborough 2010). The leader of the change implementation will need to have both the authority to make decisions and to allocate budgets in addition to overcoming fears that their own performance will be on the line if the venture does not pay appropriate dividends for the investment (Tushman & O'Reilly 2009). Another challenge is the requirement of the incumbent firm to continue to perform well under the existing model in order to fund and support the new model for the period of experimentation and implementation (Chesborough 2010).

Some of these barriers to setting up new business models allude to the human aspects of business relationships which is a significant part of the hypotheses that comprise the theory of business model innovation in incumbent firms proposed by Santos, Spector and Van der Hayden (2009). Their first two propositions are generalised to freestanding firms whilst the last two apply to corporations with a number of business units. The first proposition is that a firm's business model relies on both relationships based on activity based transactions as well as governance links between the organisational units performing business activities (Santos, Spector & Van der Hayden 2009). This leads to the second hypothesis, that is, the necessity of transformational behavioural change in those units affected by business model innovation (Santos, Spector & Van der Hayden 2009). The third hypothesis is that individual business units undergoing innovation can have impacts on the overall corporate risk and scope as well as impacting other business units. This could attract the central governance to impose constraints although benefits can also be obtained through knowledge shared amongst the units (Santos, Spector & Van der Hayden 2009).

The final hypothesis is that loose horizontal coupling of business units, mutual engagement and organisational justice will increase opportunities and reduce constraints on the BMI in business units (Santos, Spector & Van der Hayden 2009). Loose horizontal coupling allows business units to have freedom to innovate in response to local markets without restrictions and isolates risk within each business unit (Beekum & Glick 2001). Mutual engagement allows for the proposal, development and sharing of business model innovations between business units, corporate executives and business unit leaders (Santos, Spector & Van der Hayden 2009). Organisational justice is the perception within the organisation that both the processes and outcomes of decisions are fair (Tyler 1984; Lind & Tyler 1988). These four propositions have relevance to the construction industry for the larger developers/building firms (generally Tier 1 contractors), medium-size construction firms (Tier 2 contractors) and smaller construction companies (Tier 3 contractors). The implications of this theory are detailed in Table 2.4 along with the relevance to the type of building contractor.

Table 2.4 Implication of the theory to incumbent construction firms implementing BMI

Company type applicability			Implications of BMI implementation
Tier 1	Tier 2	Tier 3	
✔	✔	✔	Managers need to understand current business model before attempting BMI
✔	✔	✔	Opportunity for lean value creation
✔	✔	✔	Managers need to consider the importance of people and relationships as part of the business model in addition to technology linkage and financial exchange
✔	✔	✔	Advantages of BMI can be obtained without large capital investments, technology breakthrough, new business developments or new market development
✔	✔		An alteration in business model requires transformational behavioural change
✔			Corporate executives will need to encourage creativity for BMI to be developed in-house.
✔			Structural and behavioural change is necessary for a BMI conducive corporation
✔			The corporation will have loose horizontal coupling with mutual engagement and organisational justice

Source: Adapted from Santos, Spector & Van der Hayden 2009

Table 2.4 shows that Tier 1 construction firms can have a number of different business interests from property development, property management and construction projects which themselves may be divided into infrastructure and building projects. These building based project activities can be spread over a number of different sectors such as health, education, commercial, industrial, and residential, and there are added challenges with most projects being at different locations and often requiring different construction methodologies. This variety of complexities faced by large construction firms can lead to reluctance for transformational change, which is reflected in the industry's slow uptake of change. Project manager performance is also closely linked to time and cost outcomes so any change required to their well-known processes may be met with reluctance. These processes and methods are adopted by both project managers and subcontractors (trades) so that any change may need to extend beyond the immediate employees of the business and require training of external suppliers of labour and materials. This further adds to the workload of project managers and subcontracting staff and poses an additional risk to project success criteria.

Tier 2 contractors will often focus on construct only or design and construct projects and can often become specialised in particular sectors. There are reduced complexities in concentrating on building and limiting the development and investment units of the business. Whilst project based complexities are still relevant, these firms will have a reduced number of business units and often engage more external consultancies. This reduces internal management issues and conflict between business units but requires additional management of external resources. Project managers will need to have support from upper management in order to have the confidence to experiment with new delivery methods or construction processes generated from the new business models. Tier 3 contractors are usually involved in larger residential and smaller commercial projects and have a greater flexibility to change their methods and are often required to do so to compete in a market with easy entry and exit. The challenge for these smaller firms can be the lack of human and financial resources to draw upon when making alterations to their business strategy and/or model. Table 2.4 identified the importance for managers to understand their business models in order to be able to create or implement an innovation to them. The following section looks at the level of understanding of construction managers about business models in their own companies.

2.6.3 Business models in construction

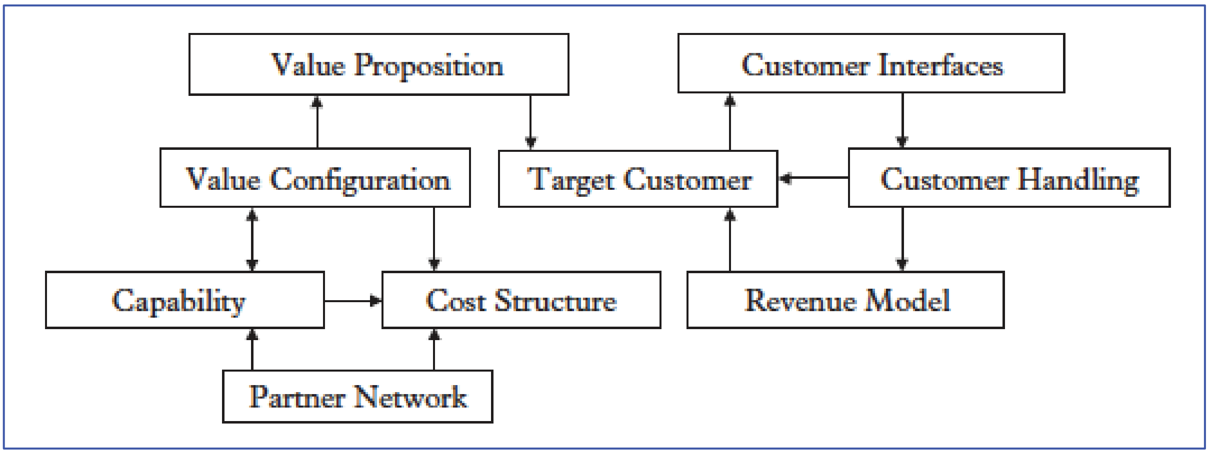
There is not a lot of literature on the development or innovation of business models in the construction industry. However, Pekuri et al. (2013) recently completed some qualitative research on chief executive officers (CEO's) and regional managers and their understanding of the business models of the construction companies they worked for in Finland. The construction companies were involved in commercial, industrial, residential, schools and nursing homes and were a combination of design and construct and self-developed projects. The managers' understanding of value creation was limited to profitability. Few managers could define who their customers were and their idea of their business's competitive advantage was limited to price (Pekuri et al. 2013). Strategy was based on geographical preference, type of project and delivery method so there was not much consideration of value creation for customers or market differentiation (Perkuri et al. 2013). The study concluded that managers in construction do not understand business models properly and fail to implement strategies to create value for their business or customers (Perkuri et al. 2013).

Not only is there a lack of understanding of business models in construction, but there is little academic research on the concept of business models in project businesses (Wilkstrom et al. 2010). The challenge of project-based business is the unique offering in different locations and for this reason projects can be viewed as independent businesses in their own environments (Artto et al. 2011). These projects will often have their own business model that differs from the business goals and objectives of the overarching organisation (Mutka & Aaltonen 2013). Having a different business model for each project creates problems in identifying the basis of successful business models due to the number of possible contributors to project success. Another challenge in creating a model that creates extra value for both customer and business is the customised supply offering in the construction industry's tender process (2002). This causes competing companies to differentiate themselves primarily through low costs and operational efficiencies but lacks attention to creating value for customers and sometimes does not even achieve basic needs and requirements (Pekuri et al. 2014). This has resulted in an atmosphere of adversarial contractual relationships rather than cooperation to increase value creation. The improvement of service levels to add value in the construction industry rather than cutting costs is one way forward to improve the performance of the construction industry (Pekuri et al. 2014). This requires not just adding value to the customer but capturing value from the added client value through business model change whilst avoiding direct price competition, which is the staple of current construction projects (Osterwalder 2004; Shafer et al. 2005).

Pekuri et al. (2014) studied three construction related companies that changed their business models to create increased value for the customer and captured revenue from this value instead of competing on price alone. The first example was an engineering firm that had a slow and inflexible value creation system and based its offering on cost and quality and charged for hours worked. They changed their model to create value through becoming responsive and reliable, with increased capabilities and offering fixed price tenders that exceeded client expectations, guarantees against legal disputes, and speedy delivery (Pekuri et al. 2014). The second case involved creating a registered process that involved a lot of upfront cooperative design process using building information modelling (BIM) which offered optimised solutions, lower total costs and early price commitment. This was suitable for complicated projects and clients looking for good service and honest dealings (Pekuri et al. 2014). The final case study involved the business creating relationships with experts and research institutions to create the best park, playground and street furniture equipment and provided both supply and service as a value capture component of the business model (Pekuri et al. 2014).

The previous discussion has shown that there is not a lot of knowledge among construction managers about business model innovation and only limited understanding of how to create value to customers and capture revenue through innovative business models in construction. There is also limited research in business models of sustainable construction and this may be due to the limited application of business models adapted for green building due to the financial risks associated with innovation in construction (Mohklesion & Holmen 2012; Brochner 2010). Mohklesion and Holmen (2012) propose a generic business model based on the existing relationships between business model elements as modified from Osterwalder et al. (2005), which is shown in Figure 2.6.

Figure 2.6 Proposed generic business model and existing relationships between its elements



Source: Mohklesion & Holmen 2012

2.7 Conclusion

The literature reveals that the concept of sustainable development is highly contested and complex, both in its definition and its application to societies in an international setting. Individual nations are implementing legislation to maximise the benefit to their constituents whilst trying to achieve targets guided by international forums. On the sustainability scale, Australia has adopted accommodating environmentalism that lies close to the anthropocentric end and further from the ecocentric standpoint.

The construction sector contributes a large percentage of carbon emissions and our nation's efforts have targeted the reduction of building operating energy. Less effort has been focused on minimising embodied energy in buildings so the increased use of timber as a sustainable building material is being investigated for its capacity as a carbon sink and low embodied energy. Uptake in timber use in residential property construction may have been slowed by consumer perceptions of its performance characteristics such as durability, structural integrity, thermal and fire resistivity.

The way in which people choose to purchase a home is also reviewed through the literature, which indicates that actual choice mimics stated preference for a home. This has motivated the survey portion of the thesis to investigate current perceptions of timber use and material preference for new homes by homeowners in Australia. Developers and construction professionals' perceptions of timber's capacity to enhance construction project success in terms of cost, time and environmental sustainability is also seen as an inhibiting factor to timber utilisation growth. The views of these industry participants in the Australian residential construction markets are also investigated.

The following chapter discusses the current use of timber in residential construction in Australia and the perception of timber use in this sector from the point of view of both a consumer and construction professional. It then reviews the barriers and opportunities for timber use in the Australian market and provides a review of the technical performance of timber as found in recent research documents.

Chapter 3 Timber use in residential construction

3.1 Introduction

This chapter reviews the literature on the current use of timber in residential construction on an international level and in Australia. On an international level the focus is on multi-storey apartment construction and for Australia it is for both apartments and detached dwellings. The review also looks at the perception of timber use in homes and apartments from the perspective of owners and occupiers on the demand side and construction professionals/developers representing the supply side. Negative perceptions of particular timber characteristics such as durability, fire and acoustics will be discussed along with some of the testing of timber performance to evaluate whether perception and reality match up. The reason for reviewing the current state of art of timber use is to identify markets in which timber use can increase in order to achieve the sustainability, time and cost goals of construction projects as discussed in Chapter 2. The current housing supply is also reviewed to emphasise the increasing market that applies to the innovative use of timber in apartment construction as well as the growing opportunities for timber in the pre-existing detached housing market that is dominated by concrete and brick construction.

3.2 Background

Timber has been used for centuries in both single dwelling residential construction and multi-unit buildings depending upon the type of resources and technologies that were locally available (Kolb 2008). The following examples demonstrate the long history of timber construction internationally:

- Italy – evidence of timber settlements from approximately 1000-1100 years BC (Giachi et al. 2010)
- Japan – traditional uses of timber construction for over 1600 years (Yokoyama et al. 2009)

- Sweden – the principal use for multi-residential construction was timber until the end of the 19th century (Mahapatra & Gustavsson 2008)
- America – softwood lumber has traditionally been the main material used in the residential construction industry (CINTRAFOR 2000)
- Australia – Timber buildings in a variety of forms have been built since British settlement (Cox, Freeland & Stacey 1980)

The benefits of using timber in residential construction have long been recognised to include low weight, high strength to weight ratio, easy to adjust on site, simple connections and high efficiency in erection, in addition to the architectural features and natural characteristics inherent in the product (Mahapatra & Gustavsson 2009; Kolb 2008; Roos, Woxblam & McKlusky 2010).

3.2.1 Timber use in Australian detached housing (BCA Class 1)

The amount of timber used in Class 1 buildings fluctuates with the number of new houses and renovations commenced each year. The Australian Bureau of Statistics (ABS) monitors monthly housing approvals, which gives a good indication of the demand for timber that may be required in Australia in a given year (Low & Mahendrajah 2010). The ABS reported an increase of 13% in private housing for the year ending June 2014 (ABS 2014). These figures conflict with house construction market research conducted by IBISworld in 2014 which recorded growth of just 4.6% for the 2013-14 financial year. Despite the conflict of data, both sources record growth that indicates an increase in demand for housing materials including timber. This is consistent with a 2013 ABARES survey of timber producers who predicted an increase in demand for sawn timber.

Another source of variations in timber use in housing is the substitution of alternative products such as concrete, metal and plastics. Timber can and has traditionally been used in most parts of a home's elements in Australia. These are shown in Table A1.1 in Appendix 1 at the end of the thesis along with the advantages/disadvantages listed for each element and the frequency of its use. Table A1.2 in Appendix 1 gives details on the varied uses of timber and alternative materials used in detached housing in Australia.

Structural elements such as wall and roof framing, decking structure and deck covering are dominated by the use of timber due to the speed of erection and cost and weight of the material. However, the use of brick as a veneer has dominated the market as the main wall material mainly due to greater thermal qualities, low maintenance and resistance to decay and insect attack (UTAS 2007). Up to 90% of new homes will have an external veneer of brickwork (IBISworld 2011). Concrete has dominated ground floor structure in the last 20 years with 80-85% usage in new homes (URS Forestry 2007; IBISworld 2011). These two material choices for floor and wall elements have become standard in most volume home companies' typical products. This perpetuates the material selection because production efficiencies are based around consistent costs and a large consumer base. With only 5.6% of new homes built predominantly out of timber products there is an opportunity for taking over part of the market currently dominated by concrete and bricks for housing envelopes (IBISworld 2011). In order for timber to take market share from heavy materials in housing it will need to demonstrate the project success factors discussed in Chapter 2.5, namely, cost, time, quality and sustainability. There will also need to be a change in the perception of timber barriers held by both home purchasers and construction professionals. This is discussed further in Section 3.3. The next three sections review the increase in multi-residential unit construction and the innovative use of timber in these projects locally and internationally.

3.2.2 Timber use in Australian multi-residential units (BCA-Class 2)

Multi-Residential Units (MRU) can be classified as low-rise, medium-rise and high-rise. The difference is generally dictated by the fire protection requirements set out by the Building Code of Australia (BCA), which is also known as the National Code of Construction (NCC). The following definitions will be used for description purposes in this thesis:

- Low-rise multi-residential will refer to unit blocks 1-3 storeys high
- Medium-rise multi-residential will refer to unit blocks 4-8 storeys high
- High-rise multi-residential will refer to unit blocks 9 floors and higher

Nolan (2009) suggested that government housing policy should encourage higher density living. This includes encouraging job growth close to the city and major metropolitan centres and increasing housing density to deal with the demand for medium- and high-density dwellings due to aging population and decreasing household sizes (NSW 2011; State of Supply Report 2010). Since 2009 there has been steady growth in multi-unit housing projects in NSW with a 41% increase in the year 2012-13 over the previous year (NSW Department of Planning & Infrastructure 2014). This growth is expected to continue with the prediction that NSW's population will grow to over 9 million by 2036, an increase of 1.6 million (22%) on the current population of 7.4 million over 23 years or close to 72,000 annually (NSW 2011; ABS 2013). A report by IBISworld in 2014 produced from a survey of construction companies found that there has been a 4.8% annual five-year growth in multi-residential unit construction that will increase to 5% in the following financial year. This multi-unit market was worth $15.7 billion in the 2013/14 year and of this materials make up close to $3.14 billion and structural wall and floor products will cost around $785 million (IBIS world 2014; Holmes 2013). The multi-unit housing market represents a massive opportunity for the increase of timber use considering it is not fully utilised in townhouse envelopes and only just starting to be used in medium-rise unit developments for wall and floor structures.

3.2.3 Current building materials used in multi-residential units

Due to the requirements for fire and acoustic resistance as well as access and egress rules governed by the BCA, most modern residential apartments are built of reinforced concrete (BCA 2012). The use of concrete columns, beams and floor plates are often mixed with brick wall infill panels and other façade materials to create appealing architectural features. This construction has evolved from units using brickwork for structural walls with concrete slabs, and columns for the parking area only. The building industry has adapted to the use of reinforced concrete and innovations for its use in residential units. This has helped to reduce time and costs with some large high-rise residential complexes achieving a six-day floor construction cycle (Watpac 2013). Post tensioned concrete enables floor slab thickness to be minimised and a reduction of reinforcing steel use that reduces material costs and building weights (Watpac 2013).

The emphasis on carbon reduction in the construction industry is only just gaining momentum and this is another reason why, until recently, heavy materials were specified in multi-residential building designs. Modern innovation in the form of engineered timber has made it possible to overcome the legislative hurdles restricting the use of timber in taller constructions through alternate solutions to the Building Code (BCA 2012). The innovation factors along with sustainability benefits identified in Chapter 2 are contributing motivations for greater interest of timber utilisation in taller multi-residential buildings. The last 6-7 years have seen an increase in the construction of innovative timber structural buildings exceeding the usual height limits of traditional timber buildings. The use of engineered timber has provided the consistency and reliability in structural performance through the negation of typical natural defects found in timber. A wide variety of engineered timber products are now in use. Table 3.1 provides a basic description of the common products utilised in some recent international timber building projects.

Table 3.1 Engineered timber product descriptions

Product Name	Product description	Common Use
Cross laminated timber (CLT)	Small sectioned lengths of timber, glued together in alternating perpendicular layers to provide dimensional stability in a structural panel	Suspended floors, Sheer walls, roof structure
Glulam	Small sectioned lengths of timber glued together with the grain parallel to produce a variety of lengths and thickness	Posts, beams, structural arches & curved members
Floor cassette	Prefabricated flooring made of a timber structure pre-decked and often clad underneath. May be insulated and a number of material components used for the non-structural elements	Repetitive prefabricated structural floor elements
Timber concrete composite (TCC)	Floor system that combines the use of timber floor joists and platform with an attached concrete layer. A lightweight alternative to reinforced concrete	Suspended floors
Oriented strand board (OSB)	Timber flakes of wood glued together in the same direction (usually longitudinally) to produce panels and beams	Panels, beams, I beam webs, floor sheeting
Structural insulated panel (SIP)	Structural panels with foam core insulation faced with outer structural material (Usually OSB).	Prefabricated wall & roof panels
Hybrid	A number of different structural materials used in combination to complete the structural elements of a building	Concrete or steel columns & beams timber floor &walls
Post tension walls/floor/beams	Tensioned steel cables that run within timber wall panels or beams adding structural capacity and seismic resistance	Structural wall and floor systems
Prefabricated walls	Walls panels built controlled conditions with either one or both facings covering the timber structural element	Structural or non-structural walls
Laminated veneer Lumber (LVL)	Veneers of glued timber layered with the grain generally in the same direction to create structural members	Beams and posts

Sources: Wood Solutions 2013; European Panel Federation 2014; Structural Insulated Panel Association 2014

3.2.4 Innovative use of timber in international projects

There are a number of reasons for the increase in innovative timber systems for larger buildings. One is the timber first policy that was introduced for government funded public buildings in Ontario, Canada, in 2012 that also increased the allowable height of timber frame buildings to six storeys (Legislative Assembly of Ontario 2012). The University of British Columbia constructed a glulam and CLT structured building for the Science Department to promote the public face of the Science Faculty (Perkins & Will 2013). Australand has recently completed the timber cassette structure of a 5-storey affordable housing project in Victoria, Australia, to obtain speed and material cost benefits compared to a traditional concrete equivalent structure (Towards Net Zero 2014). In the Swedish City of Stockholm the developer was motivated by wanting to provide affordable, sustainable living in the construction of an all timber prefabricated 8-storey apartment block (De Zeen 2014). These are just a few of the recent, innovative timber buildings included in Table 3.2 which describes a number of timber structural buildings that have been built over the last six years using a number of different systems. A variety of building types and sizes has been included although most are 5-storeys high or greater, considered tall timber buildings in some of the literature (Wood Solutions 2014). The smaller buildings have been included due to the uniqueness of their design or the innovative nature of the project for the country in which they were constructed.

Table 3.2 gives examples of international innovative projects and includes three completed buildings constructed in Australia in the last two years. The use of engineered timber such as CLT has been prevalent in Europe for over ten years but the technology has only recently been adopted by Australian companies to construct tall timber buildings (Landline 2014; Lend Lease 2012).

Table 3.2 International examples of innovative timber structural buildings

Country	City/State/ Town	Building Type	Timber Technology	Complete	Floors/ Height
Italy	Milan	Commercial/ Residential	CLT panels	2013	9 storeys
Finland	Helsinki	Residential	Mass wood modules	2014 start	8 storeys
Germany	Bad Aibling	Residential	CLT/ concrete core	2011	8 storeys
Germany	Berlin	Residential	Glulam post & beam	2008	7 storeys
Switzerland	Zurich	Commercial	Post & beam/ panels	2013	6 storeys
Sweden	Vaxjo	Residential	CLT	2009	8 storeys
Sweden	Stockholm	Residential	Timber modules	2013	8 storeys
France	Rillieux-La-Pape-Lyon	School complex	CLT/ OSB floor cassette	2013	2 storeys
Austria	Dornbirn	Life cycle tower-Commercial	TCC, prefabricated wall panels	2012	8 storeys
England	Murray Grove	Residential	CLT	2009	9 storeys
England	Hackney	Residential	CLT	2011	8 storeys
Canada	Quebec	Residential	CLT	2013	6 storeys
Canada	Richmond B.C	Remy Project Residential	OSB sheathed Sheer walls Floor cassettes	2011	6 storeys
Canada	Vancouver	University of B.C-Earth Science Building	Glulam post & beam, CLT TCC	2012	5 storeys
Canada	B.C	Elkford Community Centre	CLT, Glulam, SIP	2012	2 storeys
Canada	B.C	Commercial	CLT, Steel post and beam	2014	6 storeys
Australia	Melbourne	'Forte' Residential units	CLT	2012	10 storeys
Australia	Melbourne	Public library	Post & beam/ CLT	2014	3 storeys
Australia	Melbourne	Residential	Floor Cassette Prefab walls	2014	5 storeys
Australia	NSW	Residential	Floor cassette	2013	2 storeys
Australia	NSW	Commercial	Hybrid	N/A	(proposed)
New Zealand	Wellington	Massey University	Post tension LVL TCC floor	2012	5 storeys
New Zealand	Nelson	NMIT Arts University	Post tension walls	2011	3 storeys
New Zealand	Christchurch	Commercial	Post tension beams Concrete columns	2014	5 storeys

Source: Wood Solutions 2014; Websites of individual buildings and building companies

The growing demand for residential apartment construction combined with the capabilities of engineered timber in this building class has created the opportunity to increase the number of projects and therefore the amount of timber in apartment construction. There are, however, a number of barriers to the increased adoption of timber in residential unit projects and detached dwellings. These include misperceptions of the performance capabilities of timber, building codes and legislation, lack of education of construction professionals regarding timber performance, and the lack of incentives in Environmental Assessment Tools (EAT) for timber use. The first barrier to be discussed will be perception issues.

3.3 Perception of timber use in residential construction

With the technologies available to use timber for residential structures instead of steel and concrete, the reasons for the slow uptake of these structures require some attention. There are a number of stakeholders in the construction of new residential buildings although this section will focus on those with the most influence over the material choice used in the building. These include the developer, architect, structural engineer, and end users (Reichstein et al. 2005).

One of the main objectives of the developer when investing in large construction projects is to receive a financial return on investment. In addition, the end product that they receive needs to fulfil the particular requirements set out at the planning or design phase of the project. Semi-structured interviews and focus groups held with Swedish construction professionals by Roos, Woxblom and McCluskey in 2010 confirmed that developers were primarily concerned with cost when considering construction material and method. The exception to this objective was only of importance when aesthetic reasons held greater significance to the project (Roos, Woxblom & McCluskey 2010).

Architects have been viewed as the traditional specifiers of materials although other construction professionals can also influence the final choice for a variety of reasons (Emitt & Yeomans 2008). These include the client who may cost engineer a particular material out of a project and the project manager who may recommend particular materials for reasons of availability, cost, lead-time or ease of use. The reasons for architects specifying wood products or avoiding their use depend upon their individual perception of and education in the material options (Bysheim & Nyrud 2009; Bayne & Taylor 2006). Some of these reasons are listed below:

- Timber is highly regarded in aesthetic applications and is commonly chosen for features in multi-residential buildings (Nolan 2009)
- Timber is viewed as environmentally sustainable although this would be rated below technical reasons in their choice of materials (Wagner & Hansen 2004)
- Structural limitations reduce the likelihood of timber selection in larger buildings (Roos, Woxblom & McCluskey 2010)
- Fire and acoustic issues are viewed as difficult obstacles to overcome when timber construction is specified (Gold & Rubik 2009)

Structural engineers are responsible for ensuring that buildings maintain their structural integrity in a range of conditions. Included in the restraints they are faced with in material selection are the critical aspects of time, client preference, regulatory codes and the abilities of the other members of the design team (Knowles et al. 2010). The survey of Swedish construction professionals by Roos, Woxblom and McCluskey in 2010 found that engineers are likely to design in materials they are familiar with and materials they have been educated in regarding load-bearing capacity, that is, concrete and steel. The engineers also expressed some doubt about the on-site fabrication process and the final structural performance of timber in larger buildings (Roos, Woxblom & McCluskey 2010). Other disadvantages of the use of timber in multi-residential construction perceived by engineers include fire and acoustic resistance and the additional measures required to fulfil the associated legislative requirements (Nolan 2009).

Tenants and owners help create a market for the types of buildings constructed depending on their cultural setting and education in material properties. The use of timber is preferred by home occupants for their soft features over other aspects, although purchase price/rental price is still a major consideration (Rubik 2009). Soft features include environmental sustainability, attractiveness and the creation of a warm natural environment. According to Rubik (2009) the main reasons for consumers to prefer other materials to timber focus on its capacity to be durable. This is similar to previous research findings from a survey of 220 tenants of wood framed apartments by the Bavarian Ministry of the Interior in 2003. A phone survey by Gold and Rubik (2009) of 1004 German consumers rated fire resistance and high maintenance among timber's disadvantages as a construction product.

A survey conducted by Knoll and Company (1998) to study the perception of timber as a building material compared to concrete and steel in the USA showed that the public viewed timber as versatile, renewable, natural, recyclable, plentiful and energy efficient (Knoll & Company 1998). The same study showed that very few participants believed that timber was durable, earthquake resistant, strong or fire proof (Knoll & Company 1998). Another recent survey compared occupants' perceptions of acoustic properties against the results of technical acoustic testing in Sweden of CLT, concrete, timber and steel frame multi-residential buildings against the results of technical acoustic testing. It found that occupants had most issues with the timber frame and light steel frame although perception of CLT performance was similar to concrete although it was deemed to be the best (Ljunggren, Simmons & Hagberg 2014). The majority of the literature on consumer perception of timber use in residential construction has been conducted in America and Europe so there is a gap in the research on recent consumer perceptions of timber in the Australian setting. Lehmann and Fitzgerald (2013) identify the need to identify consumers' motivations to buy apartments built of timber in Australia after the first large scale timber residential unit project was completed at the end of 2012. Chapter 6 of this thesis presents the analysis of my recent Australian survey and interview data on the perceptions of consumer and construction professionals on timber use in residential projects.

3.3.1 Perception versus reality

The negative perception of timber use in residential construction mentioned in the previous section includes durability, structural capacity, fire resistance, acoustic and thermal performance, and insect resistance. Structural performance perception discussion is limited in this Chapter to the education issue in timber structural design. Structural design of Australian buildings is governed by the Australian Standards

AS1170 series and specific building material design such as steel, concrete, masonry and timber, and timber design guides are available. The main issue, therefore, with structural timber design in taller buildings is confidence and familiarity (CLT Handbook 2012; AS4100 1998; AS3600 2009; AS 3700 2001; AS 1720 2011). Later sections in Chapter 3 investigate in greater detail the designer's perspectives around the fire and acoustic performance of timber and the present state of scientific research on the actual performance of timber in residential construction, along with the pathway to overcoming legislative challenges. Section 3.6 reviews timber education in undergraduate construction courses in Australia. Section 3.7 discusses the durability of timber in general and some of the timber treatments.

3.3.2 Perception of fire in timber buildings

The perception that construction professionals, consumers of multi-residential apartments and the general public have regarding the fire risk of medium-rise timber buildings is generally negative. As previously mentioned, German residents surveyed by Gold and Rubik (2009) showed that fire safety of wooden residences was a large consideration when choosing a place to live and Swedish residents in a multi-storey wooden building complained about fire issues and the additional measures required to comply with building codes (Sundkvist 2008). Engineers' and architects' reluctance to specify timber in larger buildings due to fire has been documented by Ross, Woxblom and McClusky (2010) and BRE (2004). Norwegian architects, in contrast, have more confidence in timber design due to greater experience (Bysheim & Nyrud 2009). A lot of the negative perception is based on major timber building fires capturing public attention in countries such as the United Kingdom, Sweden and New Zealand despite the buildings' non-timber envelopes being a large contributor to these events (Thomas 2007; Mahapatra et al. 2008).

Fire risk in multi-storey timber structures during construction is quite significant due to the incomplete fire systems along with the large fuel loads and unenclosed areas (Koffel 2009; Bregulla 2010). Two significant timber fires during construction in the UK in 2010 reinforced the risk with damage to a 60-unit multi-residential development and the destruction of a 5-block, 5-to-6-storey residential project that required complete rebuilding (Bregulla, Mackay & Mathews 2010). Solutions to these risks can include increased security training to deal with deliberately ignited fires and early activation of fire protection measures (Koffell 2009; Bregulla, Mackay & Mathews 2010). Work health and safety officers can also prepare and implement change to workers' behaviours to avoid fire risks around hot works (WHS 2012).

Despite the concern about fire among potential occupants and owners in large timber buildings, the literature demonstrates the predictability of performance of timber and engineered timber products under fire conditions. Solid timber decomposition occurs rapidly between 200-300°C and a char layer is formed at a temperature of approximately 300°C (Konig 2005). The char layer provides protection to the internal unburned timber and this layer grows with fire progression at a constant rate pre-estimated according to international standards (Frangi, Knobloch & Fontana 2009). European timber structural design code EN1995-1-2 allocates an average charring rate of 0.65mm per minute to solid softwood timber panels/laminated panels and columns; joists and beams greater than 38mm thick are given notional charring rates of 0.7mm/min and 0.8mm/min for laminated and solid timber respectively (Frangi et al. 2009). Australian Standards (2006) has its own formula based on different timbers although the same principles are applied and an additional layer of 7.5 mm under the charred timber is considered to have no strength, so design calculations are performed considering these limitations. The capacity to make accurate calculations of timber decomposition in fire conditions allows for designs to be made compliant with the minimum fire resistance levels set out in the Australian building codes by way of engineering solutions.

International testing has confirmed the fire performance of timber floor systems (both prefabricated and built in situ) to ensure that compliance to fire resistance levels and charring rates of building codes can be achieved. Lennon et al. (2010) compared solid wood joists with OSB webbed timber I-joist and steel webbed truss joist systems and found that the engineered joist systems had comparable fire performance to the solid timber joists with appropriate fire protection linings and also offered a light weight/cheaper option.

Glulam members of various sizes and softwood species were tested for fire decomposition and all but one were found to comply with Australian Standard charring rates (Australian Standards 2006; Yang et al. 2009). Other tests include O'neill et al. (2012) who tested fire performance of LVL beam and box systems under loaded floor conditions and Frangi et al. (2009) tested charring rates of CLT. Craft (2012) conducted calculations of CLT wall panel performance and revealed that a 3-ply (114mm thick) wall panel with one layer of fire resistant plaster will have 45 minutes' fire resistance and a 190mm 5-ply CLT bare floor panel will last for 90 minutes while maintaining structural adequacy. New systems such as TCC floors of various spans have also been fire tested up to 120 minutes' structural fire resistance and modelled for use in multi-storey applications (Grant 2010; O'neill et al. 2014). Other proprietary floor systems offering 90-minute fire resistance include the Lignatur timber modular floor system and D-Dale TCC floor systems (Grant 2010).

Another challenge in achieving compliance for fire rating timber structural systems is the method of jointing. Fastening systems used in timber connections include bolts, dowels, nails, screws and other proprietary systems (Lau et al. 2010). Australian Standards (2006) deems unprotected timber connectors as having negligible fire resistance unless tested to the requirements of Australian Standard (AS1530.4). Embedded metal fasteners in timber are allocated fire resistance to the depth of effective charring for the timber element when holes are plugged with timber and connections protected by linings adopt the resistance level of the lining (AS1720.4 2006). In contrast, the Euro code 5-part 2 gives an allowance of 20 minutes' fire resistance for dowelled wood to wood (W-W) connections and 15 minutes for all other metal connections in (W-W) (EN 1995-1-2 2004).

Metal fasteners exposed to fire heat up rapidly and consequently lose strength and stiffness and also transfer heat to timber members, which speed up the charring process (Peng et al. 2010). Embedment failure of multiple dowel connections resulted due to increased charring in tests reported by Frangi, Erchinger and Montana (2010). Lau et al. (2010) tests of LVL with bolts in sheer in three applications of wood-wood-wood (W-W-W), wood-steel-wood (W-S-W) and steel-wood-steel (S-W-S) also demonstrated the negative effect of steel in wood-to-wood connections. The average fire resistance of the W-W-W was 21 minutes, W-S-W 16 minutes and S-W-S was 9 minutes (Lau et al. 2010). The diameter of the metal fasteners in dowelled connections does not seem to be significant according to Noren (1996) although the presence of nuts and bolt heads may increase the speed with which double timber connections fail (Peng et al. 2010).

Solid timber panel walls and floor plates commonly use metal fasteners for their connections and Mohammad and Munoz (2009) describe a number of connections that would suit not just CLT panels but other solid panel systems. The list below denotes a few options for both concealed and exposed fasteners depending on the additional fire protection provided in pursuing wall linings:

- Single internal spine
- Single and double surface spline
- Screwed half lap joint
- Self tapping screws
- External brackets
- Threaded rood/screw connection with wood cap
- Metal shaft with wood cap
- Concealed metal plates
- Hook joint

The amount of research and testing into fire performance is increasing although the misperception issues and building code restrictions still need to be overcome. Perception of compliance with fire performance requirements of Australia's building code for multi-storey residential construction remains a challenge for timber design and this is discussed in the next section

3.4 Fire legislation and multi-storey timber apartments

The Building Code of Australia BCA (2012) has a number of compliant timber solutions for low-rise multi-residential projects although there are quite prescriptive restrictions on the types of construction materials that may be used in residential buildings greater than three floors. Structural timber is not permitted in this scenario without an alternative solution (BCA 2012). This requires evidence that the specific design chosen conforms to the minimum requirements of the code. Evidence required by the BCA (2012) can be in the form of one of the following:

- A Registered Testing Authority report
- Certificate of conformity or compliance
- Certification with evidence by a Professional engineer or appropriately qualified person that the material, construction method or design complies with the BCA
- Certification from a product certification body accredited by JAS-ANZ (Joint accreditation system of Australia and New Zealand)
- Other documentary evidence proving a material/construction method is suitable for use in a particular building

The alternative solution must also adhere to the fire resistance levels and fire hazard properties of building components as set out in the BCA (BCA 2012). The fire resistance levels for multi-storey building structures is 90 minutes, which means the structural element must maintain its structural function for 90 minutes' exposure to fire (BCA 2012).

Having to go through the BCA alternative solution will add to the cost of these buildings through the need to design particular solutions for structural, fire and acoustic aspects. Fire resistance for these proposed buildings requires fire-engineering consultants to provide the evidence of complying construction. Until a reasonable number of these projects are complete an added premium to the cost of construction during the design phase will need to be absorbed by the developer/builder. Another option is the certification of this construction method through the 'CodeMark' scheme by a JAS-NAZ accredited body. CodeMark products/systems comply with the BCA in Australia and must be accepted by all certifying authorities nationally under state and territory legislation (CodeMark 2009). Certification lasts for three years and the process has been estimated to cost between fifty and one hundred thousand dollars. The challenges associated with fire certification are investigated through the use of interviews with construction professionals and the results are analysed in Chapter 6.4.5 of this thesis. The next section discusses the challenges of acoustic performance of timber structures.

3.5 Acoustic performance in timber buildings

The acoustic regulations in Australia's building codes aim to prevent loss of enjoyment for occupants although fulfilments of these codes don't always guarantee satisfaction (BCA 2012; Kouyoumji & Gagnon 2010). Light weight timber floors pose a problem in the low frequency impact range with thump and bumping noises generated from human traffic, bass from stereo systems, furniture movement, doors closing and mechanical services sounding (Chung et al. 2006; Maluski & Gibbs 2004; Shi, Johansson & Sundback 1995). Flanking transmission through services in walls and floors has also been identified as a particular source of annoyance to occupants in multi-storey units. (Kouyoumji & Gagnon 2010). The current perception in Australia is that timber flooring systems do not provide adequate resistance to the transmission of sound as compared to concrete elements (Chung et al. 2006).

Airborne sound insulation is rated by the measurement of transmission loss in a room adjacent to that from which noises are created, calculated according to AS/NZS ISO 717.1 (2004) and notated as Rw (weighted sound reduction index-in decibels). Impact sound is measured using a tapping machine on a floor surface above a room in which microphones pick up the remaining sound signals (Ratnala & Shrestha 2010). Australian regulations prescribe impact ratings in the form of Ln,w (normalised weighted impact sound pressure level) (BCA 2011; AS ISO 717.2 2004). The objective measurements regulated in Australian codes do not account for a number of issues faced with impact floor sounds:

- The affect of the connecting rooms' contribution to low frequency impact sound (Ratnala & Shrestha 2010)
- Tapping machine test method has been assessed by some to not accurately reflect the sounds generated by footfall and other low frequency vibration sources (Shi, Johansson & Sundback 1995)

- Laboratory testing often reports differing results to post construction testing (Kouyoumji & Gagnon 2010)
- Workmanship affects the final acoustic resistance of flooring (Trevathon & Pearse 2000)

There is no stated Australian building code requirement for floors to undergo field tests so compliance testing could be one way to overcome the underperformance of floors relative to laboratory tested solutions. The other option is to overdesign the structures in anticipation of that difference between lab and site conditions (Kouyoumji & Gagnon 2010).

A number of Australian and international innovative uses of timber provide solutions for the acoustic challenges currently facing traditional timber systems in multi-storey buildings. These include improved insulation products, solid timber panel construction, composite timber-concrete floors and prefabricated systems. A few examples are provided in Table 3.3 along with the some of the advantages and disadvantages to the introduction of such systems/products in the Australian multi-residential construction market.

Table 3.3 Timber system options for the Australian multi-residential building market

Product/ System	Can meet Australian acoustic rating	Complies with BCA 'Acceptable construction'	Advantages	Disadvantages
CLT-Cross-laminated timber	YES e.g. 'Forte' building Melbourne 2012	NO	• Lightweight • Prefabricated • No backpropping	• Requires imports • New to market • Exposure to weather onsite
TCC-Timber concrete composite	Possible-Currently used in NZ & Europe commercial	NO	• Light v concrete • Good impact insulation	• Wet trade • Time consuming • Lack of trade specialists
Sand filled floor system	YES	NO	• No wet trades • Light weight • Equals concrete acoustic levels • No backpropping	• Requires high quality control • Multiple layers of material • Expensive
Floating floor	Data not yet available	NO	• Allows under floor services • Lightweight • Heavy & light impact sound	• Multiple material layers • Requires high quality control • Australian testing required
Aerogel insulation	YES	NO	• Light & thin • performance v current product	• Cost prohibitive
Prefabricated modules	YES e.g. Parkville project under construction in Melbourne 2014	NO	• Offsite manufacture Erection speed • Quality control v onsite construction • Weather delays	• Limited manufacturers and experience • Design options

Source: Baetens, Jelle & Gustavson 2011; Gagnon & Kouyoumji 2011; Emms & Nebel 2007

Table 3.3 shows some of the options to overcoming acoustic issues with timber flooring systems. Two of these options have recently been adopted. The Forte CLT residential building in Melbourne's docklands and the Parkville 5-storey apartments under construction from prefabricated timber systems in Melbourne's outer suburbs have been through the compliance process so the developers will have some insights into dealing with the legislative barriers. The acoustic challenges for these larger timber residential buildings are discussed in the interviews and analysis in Chapter 6. The next section looks at one of the other reasons for the reluctance of design consultants to specify timber in multi-residential projects and that is lack of education and experience.

3.6 Timber education of construction professionals

Construction professionals in Australia have developed extensive experience with reinforced concrete and steel due to the dominance of these materials in multi-story apartment buildings. This familiarity provides the motivation to design and construction management professionals to specify and encourage the use of these materials early in a project. Feasibility studies are carried out at this stage to determine if the concept design is acceptable for the proposed building (Bysheim & Nyrud 2009). Project time and cost factors may motivate the exploration of alternate options later in the design phase, but proposing timber at this stage may be too late due to floor heights and support spans already being stipulated (Nolan 2009).

Mahapatra and Gustavsson (2008) in their research into breaking the construction industry's path dependency on the use of heavy materials for multi-storey construction suggest that the education and experience of construction professionals help to determine the materials used in multi-storey buildings materials. In research by Roos et al. (2010), interviews and focus groups involving Swedish construction professionals show that architects and structural engineers believe they lack the knowledge about timber to make a confident decision to use the material. The architects in the survey disclosed that 90% of their material education was on concrete and engineers revealed that their studies focused on the use of concrete for most of the latter part of their degrees (Roos et al. 2010). The Building Research Establishment revealed some time ago that lack of higher education for construction participants created a major barrier to the increased use of timber in the European Union's construction industry (BRE 2010).

3.7 Timber durability

House occupants have perceived durability as an issue associated with timber in residential housing construction as found in surveys by Gold & Rubik (2009). Durability has been defined by ABCB (2006) as the capacity of a building or the components of a building to perform a particular function for a specified design life. Design life of buildings has been categorised by the ABCB (2006) as either short (1-15 years), normal

(50 years) and long (100 years+). Houses fit in the normal design life with components that are easy to repair having a 5-year life expectancy, components that are reasonably easy to replace but costly having 15-year life spans and hard to access and expensive components are required to last 50 years (ABCB 2006). Structural timber members fit into the last category with 50-year design life and timber cladding requiring a minimum of 15 years' longevity. Whilst timber durability characteristics are the main focus of this section, factors such as service conditions, design and detailing, workmanship and maintenance also have an influence on life span (ABCB 2006). This research focuses on the natural or engineered performance of timber and presumes that maintenance, connections and fasteners, workmanship and design are implemented according to product manufacturing guidelines, building codes and acceptable standards of practice for the design/building professions and trades. The following paragraphs will discuss timber performance related decay, insect attack and weathering.

Australian Standard (AS5604) provides 4 classes of natural durability of timber for both above- and below-ground use with Class 1 timbers representing highly durable timber down to Class 4 being non-durable. Common timbers used in Australian residential construction are based on the non-durable Class 4 with the high utilisation of pine products for structural and non-structural framing, cladding and internal fit-out in both engineered and natural-sawn timber products. Increasing use of laminated and finger jointed pre-primed pine timbers in homes allows for reduced natural defects and deformations. The use of these engineered timbers increases structural capacity and ease of usability for the homebuilders. The extensive use of non-durable timbers in construction has required treatment in the form of structural detailing, chemical treatment, maintenance or a combination of these three strategies to allow for the design life of the timber element to be achieved (Crews 2003). Preservative treatments can protect timber from termites, fungi, and borers depending upon the active ingredients of the particular treatment. The Building Code of Australia requires structural members of new housing to be either naturally termite resistant or treated with preservatives (BCA 2013). Hazard classes for timber use have been documented in Australian Standards (AS1604) as a guide for specifying preservative treatments for timber in particular applications and these are found in Table 3.4.

Table 3.4 Hazard class selection guide (AS1604.1)

Hazard Class	Exposure	Service Conditions	Biological Hazard	Typical Use
H1	Inside, above-ground	Protected from the weather, well ventilated and protected from termites	Insects other than termites (e.g. lyctid borer)	Framing, flooring, furniture, interior joinery and other protected applications
H2	Inside, above-ground	Protected from wetting. Nil leaching	Borers and termites	Framing, flooring and similar uses as above
H3	Outside, in-ground	Subject to periodic moderate wetting and leaching	Moderate decay, borers and termites	Weatherboards, fascia, barges, pergola, decks, windows and door joinery
H4	Outside, in-ground	Subject to severe wetting and leaching	Severe decay, borers and termites	Fence posts, greenhouses, pergola posts, and non-critical landscaping
H5	Inside, in-ground contact or in water	Subject to extreme wetting, leaching and/ or where the critical use require a higher degree of reliability	Very severe decay, borers and termites	Piles, poles, structural retaining walls, cooling tower fill, or structural members in permanent ground contact or wet conditions
H6	Marine waters	Subject to prolonged immersion in sea water	Marine wood borers and decay	Boat hulls, marine piles, cross bracing, steps, landings etc.

Source: FWPA 2011

The three levels of classification most relevant to housing in Australia are H1, H2 and H3 whereas H4 and H5 are related to external works in construction and H6 is suitable for exposure to marine environments. H1 is concerned with internal joinery such as skirting and architraves and non-durable timber is suitable for this application. H2 is for internal above-ground uses. Timber framing and flooring is the common function for timber in this category and non-durable timbers require some protection in this situation. Under-floor structural members such as bearers and joists as well as timber cladding require durable timbers or preservative protected non-durable timbers as they have reasonable exposure to moisture. Australian standards have long lists of preservatives used for timber treatments and minimum infiltration depths for preservatives. However, this literature review will discuss only some of the commonly used timber preservative products (AS1604.1-2010).

Water based solvents with Boron are suitable for hazard levels 1 and 2 whereas Copper Chromium Arsenic (CCA), Copper Azole and Alkaline Copper Quaternary (ACQ) can be used in environments with hazard levels 1-5 (FWPA 2011). Light Organic Solvent Preservative (LOSP) is a solvent-based preservative that is used in hazard levels 1-3 (FWPA 2011). After a review of the possible harmful effects of CCA contact with the public by APVMA (2005), there are some restrictions on the use of timber preserved with CCA and as a result garden furniture, decking, handrails, picnic tables, public seating and children's play equipment should not be constructed from CCA timber and workers should use appropriate protection when working with this product. A commonly used treatment for structural house elements such as framing and cladding is the LOSP which contains fungicide, insecticide and water repellent although cladding is painted to provide additional longevity (Crews 2003). Some LOSP treatments provide a 25-year guarantee for timber framing and external products such as cladding and fascia (Osmose 2006). Other insecticides that come with substantial guarantees use synthetic pyrethoids and are mainly used for protecting internal timber framing. They do need to be reapplied to timber that has been cut to ensure protection (Blue Pine 2014).

Whilst the preservatives mentioned previously can prolong the life span of timber used in residential construction along with maintenance, detailing and good workmanship, wood modification processes such as heat treatment and chemical modification can also extend timber performance (Papadopoulos & Pougioula 2010; Palanti, Feci & Torniai 2011). These alternative treatments are receiving more attention due to the need to reduce the use of tropical woods and environmentally damaging biocides (Homan & Jorissen 2004). Thermal treatment permanently changes the chemical and physical properties of wood (Thermowood 2003). Heat treated wood has been found to decrease fungal susceptibility and increase dimensional stability as well as improving the performance of protective coverings so is well suited to external house performance. Its reduced strength, however, limits its use in structural applications and in-ground testing has produced less than optimum strength results (Thermowood 2003; Del Menezzi et al. 2008; Palanti, Feci & Torniai 2011).

Chemical modification is another wood modification process that changes the repellent nature, dimensional stability or UV resistance of timbers' cell wall polymers through chemical reactions (Rowell 2005). Chemical treatments using acetic anhydride has also been shown to extend timber product life through field testing compared to control panels in Finland, with acetylated pine showing minimal deterioration after 13 years which is similar in performance to timber treated with high levels of CCA (Brelid &

Westin 2007). Acetylated wood's dimensional stability has also implications for reduced maintenance costs for protective coatings (Kattenbrook 2007). Furfurylation is another chemical modification of timber and has shown durability against fungi and increased resistance against termites although reduced impact strength (Homan & Jorissen 2004). A study comparing the accelerated weathering of timber treated with CCA, a metal free preservative, linseed and tall oil, furfurylation and chitosan with results that all specimens showed reduced weathering against an untreated control sample (Temiz et al. 2007). Recent short-term studies in Australia demonstrated that acetylated wood has shown resistance against fungal and termite destruction with superior performance against some naturally resistant local timbers with life expectancies of over 40 years (Alexander et al. 2014).

Despite the long history of research into wood modification, commercial viability has only recently brought more attention to this process (Homan & Jorissen 2004). A number of commercial operations can be found, mostly in Europe and mainly supplying furniture, cladding, flooring, doors and windows and decking to quality markets that are not too sensitive to price competition (Brynildsen & Myhre 2007; Ala-Vikari 2007). Some agents in Australia can source thermally treated wood for external cladding (that claims to last 30 years) and acetylated wood products for window frames, doors, decking and cladding (service life 50 years above-ground) although they are not widely available at local timber yards (Accoya 2014; Thermowood 2014). This may be for reasons of price, market education and infiltration, or the product's limited structural application, yet further research of the potential for modified wood products is recommended for the Australian residential timber market to help solve some of the durability perception and performance issues.

3.8 Timber performance in earthquakes

The performance of timber in seismic regions was not identified as a major concern in the literature surveys for either design professionals or end users. It is, however, worth mentioning briefly due to the recent performance of timber systems in seismic zones, particularly after some destructive earthquakes in New Zealand. A performance review was carried out on a number of different building types of timber structures following the earthquake in the Canterbury area of New Zealand in February of 2011 (Buchanan, Carradine & Jordan 2011). Industrial buildings, school halls, swimming centres and residential homes mostly survived with little or no damage and the innovative two-storey post tensioned "EXPAN" timber building system recorded no damage (Buchanan, Carradine & Jordan 2011). Previous testing on two-storey and six-storey buildings also demonstrated the efficacy of timber structural designs in seismic activity with most damage confined to architectural coverings such as plasterboard sheeting and infill materials (van de Lindt et al. 2010; Christovasilis et al. 2007). Seismic activity causing significant death and destruction is rare in Australia compared to countries such as the USA and New Zealand, with the only significant earthquake causing deaths occurring in 1989 in Newcastle from collapse of concrete and masonry building elements (Inquest findings 1990). Post tensioned timber and CLT systems have design solutions to suit seismic zones for commercial and residential projects which could assist in avoiding some of the large scale damage in heavy material buildings seen in the recent Christchurch earthquakes of 2011 (STIC 2010; Popovski, Karacabeyli & Ceccotti 2012). The final section reviews environmental assessment tools and whilst they don't directly stop the use of timber in residential construction they focus unfairly on reducing operating energy in buildings. As discussed previously in Chapter 2.3, embodied energy is receiving more focus although this has not been reflected in voluntary or compulsory environmental assessment tools to date.

3.9 Environmental assessment tools for construction

Discussion on Environmental Assessment Tools (EAT) is relevant to the uptake of timber due to the legislative requirement for their application in residential construction in Australia. The voluntary GreenStar tool is also commonly used to market Australian commercial and residential projects. This section looks at the use of environmental assessment tools generally, for buildings in Australia and in particular the scheme that is in use in NSW for the assessment of detached and multi-residential dwellings. The purposes of EAT will be reviewed along with the benefits they provide to sustainable building. The shortcomings of currently used EAT will be examined along with some suggestions for their improvement.

Environmental assessment tools have been used in many countries to assist the construction industry to produce new buildings that have a lower negative impact on the environment. These tools have been both voluntary and legislative in their application depending upon individual states and countries (Burke & Brown, 2005). There are a multitude of EAT available for use in different classes of buildings including residential, commercial, hospitals and more recently, precinct based tools (Beattie et al. 2011). The first comprehensive EAT was UK's voluntary 'Building Research Establishment Environmental Assessment Method' (BREEAM) in 1990. Since BREEAM, many other assessment tools have been developed and adapted in countries around the world (Ding 2008). Different tools evaluate varying aspects of a building's impact on the environment such as its thermal comfort, energy and water usage. Most of these tools make up part of the planning process and are utilised in the design phase of construction projects and use predictive models to assess a building's performance (Burke & Brown 2005). This is changing with ongoing legislative progression as is evidenced with the implementation of certification systems such as Australia's NABERS system which monitors actual building performance of post construction commercial buildings.

The overriding purpose of environmental assessment tools is to benchmark and improve current building performance, primarily through design and construction, to decrease the amount of operational energy and resources consumed by building habitations (Burke & Brown 2005). Australian Government legislated EAT serve to solidify the objectives of international, federal, and state sustainability commitments through planning instruments e.g. NSW's plan to reduce 60% of emissions by 2050 (NSW Department of Planning 2011) and energy targets for government building use (Commonwealth Government 2007). Individual states currently implement their own requirements for sustainable residential building, which creates challenges for developers working in multiple states. Voluntary EAT in the construction sector rely on the desire of developers, clients, building companies and consultants for best practice and possible market differentiation to drive the use of such tools. This has occurred with the 'Green Star' EAT which has become more common practice amongst commercial building builders and there is competition to achieve the highest star rating to promote sales and developer/construction company image (GBCA 2014).

There is a number of different EAT for buildings in Australia depending on building class, regions and particular aspects of a building's performance. These tools are often updated and extended to different building classes and new tools are continually introduced into the market. Table A1.3 in Appendix 1 provides some examples of the common tools used in Australia. Sustainable building legislation exists to benchmark some of the requirements for the design and use of residential, commercial, and public buildings. This takes place through mechanisms such as the Building Code of Australia (BCA), individual state planning regulations and local government requirements. In addition to BCA requirements, mandatory environmental assessment tools were introduced in 2011 for Australian commercial buildings (NABERS' building energy certificate) and in 2004/05 for NSW residential/multi-residential buildings (BASIX).

The BCA requires that new building work Australia wide must achieve certain energy efficiencies through mechanisms such as insulation, air infiltration control, glazing and shading. Dwellings can reach compliance by using the acceptable construction methods set out in the BCA or by achieving a 5-6 star rating, and locality of the building will dictate minimum star requirement (BCA 2011). This rating is generated by thermal simulation software that meets the Australian Building Codes Board's protocol for house energy rating software and is accredited by NatHERS (National House Energy Rating Scheme). The tools that are currently accredited by NatERS are shown below:

- AccuRate (version 1.1.4.1)
- AccuRate Sustainability (Version 2.9.2.13)
- BERS Professional (Version 4.2.110811)
- First Rate 5 (Version 5.1x)

The BASIX certification is NSW based and began in Sydney in 2004 with new-detached houses and guest/boarding house developments and was extended to new multi-residential buildings in 2005. House renovations over $50k are also required to comply (NSW Planning 2011). A 40% reduction of the benchmark energy and water allocation per person must be achieved through design, building insulation, water heating/onsite reuse selection and electrical/water fitting and fixture choice (BASIX 2015). A compliance certificate is issued once the minimum targets are met and this forms part of the development application. The Principal Certifying Authority (PCA) for the development is required to ensure that commitments made prior to construction are built into the finished product. This is achieved through the provision of a BASIX completion receipt by the PCA before they issue a final occupation certificate (NSW Planning 2011). A 2013 University of Canberra BASIX user survey found that thermal assessors and building professionals considered the tool to be reducing water and energy use although they recommend some improvements to the tool (Planning and Infrastructure 2013). These include educating the market that the use of sustainable construction materials can be cost effective, integrating BASIX with national sustainability requirements, and ensuring that sustainability assessment should be over the building's life span and include material choice and embodied energy (Planning and Infrastructure 2013).

It is also generally agreed that the use of environmental assessment tools contributes to the goals of sustainable construction and that benefits are gained for both occupants and owners of buildings that have been built to minimise environmental impact (Ding 2008; Owen 2006). In addition to the benefits of building sustainably, there is an imperative both through legislation and social responsibility to limit the impact of the built environment on the natural environment. The debate is not whether environmental assessment tools will be used but rather which tools are the most suitable and the how particular issues with the current tools need to be addressed. Table 3.5 identifies some of the problems raised by various stakeholders of the green building process plus the advantages for building owners/tenants. The contents include both Australian and international opinion.

Table 3.5 Stakeholder views of environmental assessment tools and the construction impact

Issues and Barriers
A) TOOLS
1. No tools to compare different solutions at feasibility phase. 2. Tools are too complex and require too much data. 3. Tools are limited in their scope. 4. EAT usually implemented near design completion making it too late/expensive for many changes 5. Cost of using tools not limited to certification, new products, systems, and construction methods. A lot of hidden consultant costs. 6. Many tools fail to address cost, social implications resource use and impact on the natural habitat 7. EAT does not address habits of occupiers 8. Majority of tools only address new buildings or refurbishment. This covers only a small percentage of all buildings. 9. No quantifiable cost database for the implementation of sustainable inclusions for the different tools. 10. Embodied energy and disposal not accounted for in the assessment tools. 11. Precinct issues not covered by tools 12. End use monitoring is rare and not correlated to specific sustainable inclusions derived from tools 13. Majority of tools only address new buildings or refurbishment. This covers only a small percentage of all buildings.
B) DESIGN
1. Longer design time (earlier integration required) 2. Lack of experts to lead design teams from project initiation 3. No incentives for designers to include sustainability if no mandate. 4. No tools to compare different solutions at feasibility phase. 5. Extended planning/approval process 6. Lack of integrated design methods 7. Inadequate incentives for designers to develop skill base
C) CLIENTS/DEVELOPER
1. Nil readily available knowledge of cost risks 2. Lack of comprehensive information about new solutions 3. Financial benefits mainly received by end user rather than client/developer 4. Industry perception that sustainability will increase construction costs 5. Sustainable building considered too complex/ additional work by developers, owners & contractors 6. Use of different contracts (client/contractor/subcontractors/suppliers) 7. Cost benefits from energy efficiency little known 8. Most buyers do not want to pay extra upfront 9. Sustainable buildings don't increase property values
D) CONTRACTOR
1. Lack of Contractor knowledge of construction impacts of sustainable building 2. Difficult to accommodate new processes, site planning, work methods and worker behaviour 3. Lack of contractor understanding of embodied energy and water in substitution materials 4. Limited availability of sustainable products & materials and related information 5. Absence of uniform product and material rating systems 6. Resistance of subcontractors to implement changes
Benefits of environmental inclusions in buildings
1. Improved building sale price 2. Increased demand from prospective tenants (Easier to let) 3. Increased rental returns for building owner 4. Improved indoor air quality leading to increased productivity of tenant's employees 5. High profile building enhances developer/builders reputation. 6. Decreased running and maintenance costs 7. Suitable for tenants which have corporate policies requiring triple bottom line reporting

Source: GBCA 2014; Ding 2008; Hakkinen & Belloni 2011; Tredrea & Mehrtrens 2008; Burke & Brown 2000

As can be seen in the table above many negative impressions are held about the tools used to assess sustainable buildings and there are also some conflicting views of these tools amongst building stakeholders. However, a growing number of building companies and owners are using voluntary tools (e.g. Green Star) in Australia and mandatory tools are expanding to cover more types of buildings and gradually increasing sustainable criteria requirements. Post construction building performance evaluation is gradually evolving in Australia with NABERS for large commercial buildings and BASIX for residential buildings. Some general improvements could be made to existing tools and these are listed below:

- Include embodied energy into mainstream mandatory and mainstream voluntary tools (GBCA 2014)
- Ensure EAT are geared to early stages of building/development projects to allow assessment of different options prior to detailed design
- Enable design and costing tools to be integrated into EAT through Building Information Modelling (BIM) tools
- Provide increased education to clients/developers/contractors/designers through tertiary education, government and private courses (Planning & Infrastructure 2011)
- Provide material/product databases that integrate with existing mainstream EAT
- Provide tax/financial incentives to developers/clients/contractors and property buyers to invest in sustainable buildings

3.10 Conclusion

This chapter has identified the growing number of innovative multi-storey structural timber buildings internationally. It also reviewed the current uses of timber in detached residential buildings in Australia and opportunities to increase its market share. Among the opportunities in detached homes to increase the use of timber are floor substructure and wall veneer. Opportunities in multi-storey residential buildings can be found in structural walls and floors. Expected growth in the construction of housing is also presenting opportunities for greater use of timber.

The main areas of negative perception of timber were identified in the literature as being its performance in relation to durability, fire, acoustic, structure, unknown costs and return on investment. Research has shown that fire, acoustic and durability issues can be overcome. However, legislative challenges and high costs remain a concern. The supply side also lacked confidence in proposing timber. Lack of education about its performance and benefits is seen to be hindering the increased uptake of the use timber in addition to legislative barriers in building codes and standards. Environmental assessment tools could also be reviewed and updated to reflect the environmental sustainability benefits of certain materials over a building's life cycle.

The following chapter delves into life cycle analysis and life cycle costs and reviews the current literature that has used timber in life cycle case studies. Construction time is also investigated in some detail along with thermal analysis of residential developments.

Chapter 4 Construction Performance indicators

4.1 Introduction

Chapter 2 discussed the concepts of sustainability and their relevance to the Australian construction industry and identified the use of timber as a means to improve sustainability in residential buildings. Chapter 3 investigated and analysed the sustainable characteristics of timber and the current use of timber in residential construction both locally and internationally, and discussed the current state-of-art of timber use in construction. This chapter will look at the assessment of sustainability in residential development and will review the current main performance indicators of successful construction projects, namely time, cost and quality (primarily thermal envelope performance) in addition to sustainability, which has been established as a new component of performance in construction. The focus will be on frameworks and tools used to calculate, assess and compare construction performance in residential projects. These tools include life cycle analysis (LCA) for sustainability, and life cycle costing (LCC) for cost, time performance and thermal analysis. There will also be a review of the current literature and case studies that contain analysis of these particular performance criteria.

4.2 Sustainable performance – Life Cycle Analysis (LCA)

This section reviews the history and purpose of LCA assessments as well as different LCA models and then looks specifically at the application of timber and heavy material in LCA studies comparing timber and heavy materials in the Australian residential construction sector through the discussion of some literature based case studies.

4.2.1 LCA overview

Life Cycle Analysis (LCA) is thought to have originated in 1969 when Coca Cola conducted the very first LCA study to compare the difference between using plastic and glass bottles (ARUP 2007). These first studies were equivalent to current Life Cycle Inventories (LCI) because they lacked the impact assessment that is part of modern LCA (ANSI/ISO 14040 2006). The reasons for the development of LCA were the problems with rising waste accumulation, and the acknowledgement of limited resources and energy supply issues (Klopffer & Grahl 2014). It wasn't until the late 1980's and early 1990's that LCA models began a process of standardisation (SETAC 1993). Lei, Zhifeng and Fung (2003) describe LCA as a quantitative method used to assess the environmental burdens of particular products or systems over their entire life cycle. LCA models are used to measure the total impact of a particular product on the environment from when the raw materials are extracted from the ground all the way through to when the product or system is terminated. Whether disposed of or recycled at the end of its life, this is commonly known as the life cycle from a cradle to grave/cradle perspective (ANSI/ISO 14040 2006). All the processes of a particular product or service that compose a product system make up its life cycle and can, therefore, be compared to other product systems that perform an equivalent function (SETAC 1993). The function or purpose of a product is known as a functional unit and in construction a common unit used for buildings is square metre (m^2) of floor area (Klopffer & Grahl 2014). Product systems consist of a number of stages. The 'Consultancy Study on LCA of building construction' published by Arup in 2007 outlined the five main stages relating to a building:

- Raw material acquisition
- Manufacturing & delivery
- Construction phase
- Operation and maintenance
- Demolition/end of life disposal

Lei, Zhifeng and Fung (2003) note that LCA studies have numerous useful applications for companies. They provide data and information about a particular product system, which allows companies to have an understanding of the impacts that their product has on the environment and potentially to increase the credibility of their environmental policy (Peuttmann & Wilson 2005). LCAs are also used by companies to work out ways to make their production process more efficient as well as guiding suppliers of inputs for their product to act in a more environmentally sustainable way. Challenges associated with LCAs for buildings are that they contain a number of stages and each of these stages has a number of variable inputs including material suppliers, manufacturing processes, delivery modes, energy suppliers, maintenance and demolition (Lee, Tae & Shin 2009). In addition to these challenges specific to construction, there are also limitations such as necessary hypotheses, imperfect data, adaptability issues and high costs (Lei, Zhifeng & Fung 2003). As there are many different LCA models they are each prone to particular challenges so the method should be chosen to suit the particular product or system environment (Lee, Tae & Shin 2009). A discussion on some different LCA models is included in Section 4.2.3.

4.2.2 International standards for LCA studies

The first International Standards Organisation (ISO) standard for LCA was released in 1997 to address concerns over inappropriate use of LCA by companies in the early 1990's that were making broad but inaccurate claims about their products for marketing purposes (Curran 2008). In addition, pressures from numerous environmental organisations to standardise LCA methodology, and to combine all the various LCA guidelines that were appearing on an international level into one guideline, led to the development of the ISO 14040 series. The introduction of these international standards was seen as a milestone for LCA practice, although they are not completely suited to every methodological choice in LCA (Ekvall 2002a). The generic nature of the framework also allows analysts to use the standard and produce virtually any LCA result to suit their aims and objectives (Ekvall 2002a). Another issue of the standard discussed by Ekvall (2002a) is the quickly evolving nature of LCA methodology that leads to out-dated standards. This requires the standards to be updated by the ISO to ensure new ideas are continually incorporated into the guidelines. ISO 14040:2006 is the most recent International Standard for LCA and it outlines the requirements that are needed to conduct an LCA. It provides a distinct framework that LCA practitioners can follow when conducting an LCA. The standard breaks an LCA study up into 4 main steps:

- Defining the goal and scope - level of detail, scope & system boundary

- Creating the inventory - Involves collection of input/output data
- Assessing the impact - Evaluation of potential environmental impacts and estimation of resources used.
- Interpreting the results - Evaluate findings and issues into a final report

In order to assess the impacts of a building on the environment, its components, and the energy to produce and maintain its components in addition to the energy to operate the building, need to be calculated throughout the whole life cycle of the building (Bribian, Uson & Scarpellini 2011). Whilst the international standards provide guidelines for LCA, no single standard model or approach is used for all LCA studies and many models vary significantly in their approaches (ISO 14040 2006). Many LCA practitioners view this standard as a generic framework to assist them to produce unique LCA models that will be specific to their particular wants and needs (Ekvall 20002b). The information produced from LCA studies can be instrumental in providing information regarding environmental impacts of products although they do not address a product's economic, social or technological aspects (ISO 14040 2006).

4.2.3 LCA models

A number of different LCA models are available for use depending on the type of product, product system and stages of a products' life cycle. Some LCA models investigate a single product, other LCA models will investigate the relationships associated with a particular product or system, and still others will be used to compare different products. Table 4.1 gives a brief overview of some of the common LCA models along with their advantages and limitations.

Table 4.1 Overview of some common LCA models

LCA Model	Purpose	Advantages	Limitations
Process based LCA	Particular product and its manufacturing process	Detailed analysis of the process. Good in product comparison	Scope boundaries difficult to define. Multiple truncation errors possible
Input/ Output	Include all the relationships in the manufacturing process.	Accounts for complex interactions between industries. Assumes set input levels form other industries	Input data often out-dated. Imported products assumed to have same impact as local products
Economic input/output (EIO)	Overcome limitations of boundary definition	Broad scope/ entire supply chain included/ small emissions & transactions included	Limited no of impacts included / impact assessment not included
Most of the most	Focuses first on major impact factors-then on the significant phases	Addresses scope definition and boundary issues. Simpler method. Good feedback for product designers	Limits the size of the LCA
Attributional LCA	Provides impacts of products entire processes and disposal	Effective for product comparison. Allows for product stage improvement	Doesn't address indirect effects on the product life cycle
Consequential LCA	Focuses on effects of changes to product output	Can identify effects of change both inside and outside of product life cycle. Allows analysis of effects of production change.	Accuracy of forecasting change effect is limited. Decision makers often want to know actual impacts rather than potential impacts of change
Building Material Eco. Sustainability (BES Index)	Assessment of 30 commonly used construction materials	Allows for comparative ecological impact. Useful for design stage when contemplating material options	Doesn't include different performance aspects of alternate materials e.g. thermal.
Tiered hybrid model	Upstream and downstream processes analysed by different methods	Complete and accurate results quite quickly	Requires careful selection between up/downstream. Double counting errors. Interaction between processes hard to distinguish
Input-output hybrid model	Hybrid analysis by separation of industry sectors	Comprehensive results	Complicated to perform. Interaction between processes hard to distinguish
Integrated hybrid analysis	Integrates the two methods of analysis	Complete results, no double counting	Complex analysis

Source: Eckvall 2002b; Suh et al. 2003; Suh & Huppes 2005; Kent 2007; Brander et al. 2008; Finnveden et al. 2009

Table 4.1 provides a number of different approaches to LCA, each having advantages and disadvantages for particular product applications and industries. The following discussion will focus on the process based LCA method and input-output LCA method.

These are the main methods used to account for the environmental impact of goods and services and are the foundation for many of the hybridised methods (Horvath 2004; Majeau-Bettez, Stromman & Hertwich 2011)

i) Process based LCA

The process based LCA analysis method is seen as a conventional approach to LCA that is aimed at the manufacturing process of a product, where all the inputs and outputs for a particular product are itemised (Rowley, Lundie & Peters 2009). Two main process based approaches are used, namely, process flow diagrams and matrix representation of a product (Suh & Huppes 2005). The process based approach is a 'bottom up' technique where the resource requirements and the pollutant releases from the main production processes as well as any important contributions from the suppliers of inputs into the main process are assessed and analysed in detail (Lenzen 2002).

The process based approach consists of an LCA analyst reviewing in detail the various resources used as well as the environmental releases from the suppliers of inputs that are considered to be of significance (Suh et al. 2003). The analyst determines an initial system boundary or scope for the LCA study, as it is referred to in ISO 14040 (2006), which is then further refined as additional unit processes are found to be important by sensitivity analysis (Suh et al. 2003). The advantages of the process LCA method include the specific application to one area of a product process, ease of comparisons between products, and identification of manufacturing process weaknesses. This allows for process improvements to occur as well as future product development assessments. Limitations of this model include scope development challenges related to setting a boundary that is too large (creating an unreasonable amount of work) or fails to account for many major activities due to a boundary that is too small (Majeau-Bettez, Stromman & Hertwich 2011). This method can also require high resources and labour, making it quite an expensive process due the large volume of process specific primary data (Rowley, Lundie & Peters 2009).

ii) Economic input/output LCA method

The input output approach was designed to capture all the economy wide interdependencies but it wasn't until the 1970's that Leontief proposed using the input-output approach to analyse environmental impacts (Rowley et al. 2009). Applications of input output analysis started being used in LCA analysis in the early 1990's (Suh & Huppes 2005). The input output analysis is a 'top down' macroeconomic technique which accounts for the complex interdependencies of industries within modern economies through the utilisation of sectoral monetary transactions data (Majeau-Bettez, Stromman & Hertwich 2011).

The use of input output analysis came about as an alternative to the process based method due to the fact that in a modern economy all processes are either directly or indirectly connected with each other. In a process based analysis, truncation errors continually occurred, because it was not viable to obtain process specific data for an entire economy (Suh & Huppes 2005). These truncation errors in the processed based analysis occur due to the delineation of the product system under study by a finite boundary and the omission of contributions outside this boundary (Majeau-Bettez, Stromman & Hertwich 2011).

Several limitations associated with the input output method need to be addressed. Firstly, input output tables are usually published with a delay of a couple of years. This varies between different countries though is true for Australia (Rowley et al. 2009). The primary reason for this delay is that as the input output tables cover the entire economy, a plethora of data needs to be processed. Coupled with the fact that in most cases statistics are usually sensitive and inaccessible to the general public, this means that it often takes a few years before a table is officially published. Another issue with input output analysis is that in essence it is concerned with the production phase only; hence it is typically used in life cycle inventory (LCI) analysis (Rowley et al. 2009). This issue has been addressed through the development of the WIO model produced by Nakamura and Kondo (2002), which closes the loop of life cycle with the framework of input output analysis. The final challenge in using the input output is the variation of detail and lack of compatibility between international input output tables, which create difficulties when assessing a variety of inputs from different countries (Suh a& Nakamura 2007).

This section provides an overview of the purpose and guidelines and some benefits and challenges associated with LCA and investigate some of the methods used in LCA. It demonstrates the many and varied difficulties in conducting LCAs for product systems and the added complexities related to LCAs of buildings that have different locations and a variety of material supply options and delivery location options. The next section will review some of the studies completed for buildings and building materials both for life cycle inventories (LCI) and LCA. It will cover both the international and local context for buildings.

4.2.4 LCA in the building industry

LCA is a term used fairly loosely. The common types of LCA or partial LCA include cradle to gate, gate to gate, cradle to grave and cradle to cradle. Cradle to gate is from the stage of extraction to product completion (excluding distribution), gate to gate includes one section of the manufacturing process, cradle to grave includes the whole life span of a material from extraction through use and disposal, and cradle to cradle involves all the processes from extraction to end of life of a product with the addition of recycling (Peuttmann & Wilson 2005; Mitchell & McFallan 2008). A number of early environmental building material studies were based mainly on partial LCAs or cradle to gate studies before particular guidelines were introduced to allow for comparable studies based on fixed criteria (Buchanan 1993; Arima 1993; CORRIM 2001). These include the comparison of wood, steel and concrete when used in houses that resulted in lower embodied energy of 50% for the timber home over the house with concrete floors and steel frames (Glover 2002). Another cradle to gate study investigated materials used in window frames. This study found that timber window frames required less energy to produce than PVC and aluminium window frames (Mohammad & Welling 2002). More recently, a life cycle inventory (LCI) was completed for Australian timber products (Mitchell & McFallan 2008). Puettmann et al. (2010) also documented a cradle to gate comparison between hardwood and softwood manufacturing and the result showed softwood required 50% less energy than hardwood. These cradle to gate studies are a useful source of data and add to the accuracy of whole building LCA as they continually improve.

As mentioned previously, buildings vary in shape, size, location and material composition and require a number of processes to convert raw materials into a building that may last a vast number of years. It also requires operating energy, maintenance during its useful life and demolition at the end of it. Calculating the energy for all these activities is known as life cycle energy analysis (LCEA) and is the last step prior to performing the impact assessment of an LCA. Ramesh, Prakash and Shukla (2010) split the LCEA system boundary for buildings into three phases. These are the manufacturing, use and demolition phases and are shown in Table 4.2 with the more detailed processes listed.

Table 4.2 System boundaries for the LCE of buildings

Manufacturing Phase	Use/operating phase	Demolition/end of life phase
Raw material mining	Heating and cooling	Building demolition
Building material production	Hot water	Transport
Transport	Lighting	Landfill/recycling
Building shell construction	Appliances	
Renovation/maintenance		

Source: Adapted from Ramesh, Prakash & Shukla 2010

Table 4.2 provides an overview of the typical energy sources for a building LCEA. However, depending on the purpose of the study, certain aspects may be omitted. Some examples of these exclusions include the power required to operate power tools or cordless tools, transport for workers from home to site, and particular materials that have not yet been allocated production energy values due to recent innovation or availability (Gustavsson & Joelsson 2010). A couple of reasons for excluding parts of the LCEA can include a lack of reliable information or the process/material is not required for comparison purposes. Any exclusions or assumptions in LCEA or LCA are identified in the first part of the LCA that defines its goal and scope by providing the level of detail and system boundary of the study (ISO 14040:2006). The following section will discuss some examples of LCA research that is specific to Australia and focuses on residential development.

4.2.5 LCA studies for residential development

This section will review a few recent residential LCA studies conducted in Australia using timber as the comparative material to the heavy building materials. There are a number of reasons for selecting these studies. Firstly, they provide a basis for assuming that timber can perform equally or better than heavy materials in the Australian context, which is the focus of this thesis. Secondly, the detached homes discussed below provide a similar point of comparison to the proposed LCEA of ten case studies for this thesis. Thirdly, the LCAs are recently completed projects that are representative of the typical volume-produced homes using techniques and processes that will be replicated in this study. Finally, the multi-residential case is the first in Australia and largest in the world for its type of construction methods.

The first LCA study concerns Australia's first and largest Cross Laminated Timber (CLT) building completed in 2012 in Melbourne. It stands ten storeys high and was built on footings of concrete piles and reinforced concrete ground floor and first level flooring. The remainder of the structure (walls, floor and fire stairs) was built using platform construction from panels of various thicknesses of CLT imported by sea from Austria. The peer reviewed cradle to grave LCA of the CLT building included the operating energy made up of HVAC and lighting, material production and transport (including material extraction processes), and end of life material disposal and these were all compared to a reference building of similar design using reinforced concrete as the main structural material (Durlinger, Crossin & Wong 2013). The functional unit of the study is one square metre of residential and retail space complying with current building codes and given a life span of 50 years and the study excluded internal fittings and fixtures (Durlinger, Crossin & Wong 2013). The results showed the timber building having 13% lower global warming potential than the concrete reference building (or 22% if sequestration is included), 12% lower eutrophication, lower water usage by 2%, and 16% less non-renewable cumulative energy demand (Durlinger, Crossin & Wong 2013). Looking at materials from a cradle to gate perspective, the timber building outperformed the concrete building with 30% less global warming potential (Durlinger, Crossin & Wong 2013).

A study by Carre (2011) consisted of an LCA comparison of a typical house with concrete slab with brick veneer wall to a number of alternative designs, one with steel framed walls with brick veneer both elevated and on a concrete slab and another with a timber floor and wall structure with timber frames and timber cladding. The comparison compared one metre squared of GFA (including the garage) of which 76% was climate controlled and included materials, construction, operation (heating and cooling) and maintenance as well as end of life waste treatment (Carre 2011). The design used was based on a typical Housing Industry of Australia (HIA) design of three bedrooms and two bathrooms, with a floor area close to 200m2 and a life expectancy of 50 years. Overall LCA results showed that the homes with timber floor and wall structure with timber cladding had less global warming potential (GWP) than the homes with concrete slabs, steel frames, and brick veneer (Carre 2011). Just looking at the life cycle of construction types, the home with elevated timber structural floors and timber wall envelope was 9% less GWP than those with concrete slabs with brick veneer envelopes (Carre 2011).

The third comparative Australian LCA case study was conducted by Ximenes and Grant (2013) in Sydney and compared two common house designs of brick veneer and concrete floor to a redesigned timber maximised house for a life span of 50 years. The functional unit was one metre squared and the base cases included a one-storey, four bedroom house with 221m^2 floor area and a two-storey, four bedroom house with 296m^2 floor area. The LCA included material production (extraction, transport and processing energies), material transport to site, maintenance and repairs, as well as construction and end of life waste (Ximenes & Grant 2013). Operational energy (heating and cooling) was presumed to be same in both case study designs on the basis that comparative timber redesigns achieved the same star rating through the energy modelling software accepted by Australia's building code, AccuRate. The use of timber resulted in an approximately 50% reduction in GWP for both the one- and two-storey homes when compared to the original concrete floor and brick veneer design. However, the study did mention that end of use landfill carbon storage in timber contributed significantly to the result (between 40-60% of the timber design's overall life cycle GWP) (Ximenes & Grant 2013). The problem with this study is that its results need that end of life scenario (carbon storage in landfill) to demonstrate that the timber redesign homes have less GWP than the concrete and brick base case. Moreover, only two case studies are used to compare traditional heavy material design to the timber-optimised design. A further limitation is that a brick external envelope was used for all scenarios and timber optimisation was based only on floor structure and covering, window frames, internal wall frames and roof frames. Finally, the sites used for the study were both flat although this is not the case for many suburbs in Sydney.

These three studies based in the Australian construction context present results favouring timber over heavy materials in GWP despite each being limited in number and scope. Based on these cradle to grave studies and previously mentioned cradle to gate studies, timber appears to provide a benefit in terms of reducing environmental impact compared to heavy materials although a larger study would help consolidate these results. The other performance indicators investigated in this study included cost, time and quality. The next section will look at the literature on life cycle costing.

4.3 Life Cycle Cost Analysis

Life cycle costing (LCC) is a calculation method to support a financial decision that is usually based on weighing up a number of options. LCC found its origins with the US Department of Defence when it attempted to track long term cost effects of purchasing decisions (White & Oswald 1976). This method of costing is mainly used in defence and construction, but there is a slow adoption in other industries (Lindholm & Suomala 2005). It assists owners, users and managers to make upfront decisions regarding asset acquisition that will affect the cost over the life of the asset (Commonwealth of Australia 2001). This is critical as ongoing costs of asset operation, repair and maintenance can often be greater than the upfront purchase price, which is precise (Commonwealth of Australia 2001). LCC in the construction industry covers the cost of a building through its entire life cycle from the construction, through operation and maintenance and finally deconstruction and/or waste disposal. Prior to the use of LCC in the construction sector, building projects were analysed and selected primarily on the basis of the initial cost of construction and did not consider costs that occurred during the remainder of the building's life (Highton 2012). The issue with considering only the upfront building costs is that it creates an emphasis on profits, which in turn leads to cost cutting in the areas of material quality and workmanship (Ellingham & Fawcett 2006; March 2009). The roll on effect with omitting to consider a life cycle strategy could lead to an increase in the use of resources due to implementing cheap but inefficient heating and cooling system, and lighting solutions and materials that require more frequent repair and replacement (Ashworth & Hogg 2007).

This increases the cost of running and maintaining these buildings. The increase in energy costs related to HVAC and lighting, labour and parts for maintenance and the growing interest in reducing the environmental impacts of buildings, places more importance on the entire building costs over its life span. For example, retail energy prices rose 104% in NSW over the 6 years to 2013 (IPART 2013). Due to high operating costs, owner/occupiers have pushed for higher efficiency in not just lighting and HVAC systems but are looking towards envelope design and use of materials in the structure to provide cost effective and high quality indoor air environments (Highton 2012). The government has introduced energy reduction targets for their own buildings as well as requiring large commercial building owners to provide energy efficiency certificates to prospective tenants and buyers of their property through the NatHERS scheme introduced in 2011.

The increase in the use of LCC in choosing building designs that both reduce life costs of buildings and their negative impact on the environment has led to the construction of buildings that have a higher upfront cost but lower operating costs. The council office building CH2 in Melbourne is an example of increasing upfront costs to reduce life cycle costs. An extra $11.3 million dollars was spent upfront to achieve annual savings of $1.2 million dollars (Commonwealth of Australia 2011). A 27-storey residential tower in New York reduced the annual energy and potable water use by 35% and 50% respectively with an upfront additional cost of $17 million on the $97 million base price (NRDC 2004). These figures show the benefits of approaching buildings on the merit of their cost over their life span rather than just the original build price. LCC provides the benefit of being able to compare design options at the feasibility and design stage prior to making a commitment to initial capital costs (Highton 2012).

A few important issues with the use of LCC include the validity of available information for use in LCC, cost prediction accuracy, and the end of life costs (Lindholm & Suomala 2005). There are a number of other problems associated with LCC some of which are listed in Table 4.3.

Table 4.3 Issues with life cycle costing

Issue	Description
Lessons learned	Initial LCC estimates rarely compared to actual costs leading to a lack of information for future projects
Costs	The cost of collecting data. Systems or people are required to continually update information
Business longevity	The company that initially purchased or moved into the building may not remain for the life span of the building
Unreliable data	Data used for initial estimates may not be reliable or applicable to the product or building subject to the LCC
Innovation/legislation	Innovation in products for repairs, energy provision, and change in legislation will affect the actual cost
Maintenance schedules	Building maintenance may not be implemented according to original maintenance schedules
Owner v tenant	Initial client may sell the building on completion and keep data from future owner
Life cycle time	For products/projects with long life cycles e.g. 50 years, the records may be lost or misplaced
Proprietary information	Business may not share the information public or within the industry

Source: Jarvinen 2004; Wouters et al. 2005; Lindholm & Suomala 2005

Table 4.3 shows some of the challenges associated with using and evaluating the costs of products and assets over a lifetime. The particular challenges associated with buildings are those related to long life spans, particularly of 50+ years. This makes it challenging to keep accurate data. Occupants often change during this time leading to different building management practices and data collection techniques. The initial estimates of LCC are also likely to remain with the client and building company if the building is sold at completion. For these reasons, in addition to LCC being used to cover approximately 50 years, there is a lack of empirical LCC data for buildings including the initial estimate of LCC and actual costs for the life of the building (Lindholm & Suomala 2007).

One of the common uses of LCC is in the comparison between two products, particularly relevant to the construction of buildings for client occupiers who are looking beyond the initial construction cost (Korpi & Risku 2008). Korpi and Risku (2008) conducted a review of academic literature from 43 journals and only found 55 suitable LCC studies. The majority of cases (55%) were in the construction industry and the majority of LCC in these studies were client driven (Korpi & Risku 2008). Building costing can engage a variety of methods including detailed costings, elemental costing, and comparative costing using cost databases or in-house proprietary information (Rawlinsons 2012). Calculating costs and revenues over the life of a business or project can involve the use of net present value (NPV), internal rate of return (IRR), and payback period (Lindholm & Suomala 2007). The government of Australia recommended using NPV for the calculation of future costs for government managers responsible for procuring buildings or other major capital items (Commonwealth of Australia 2001). NPV will be used in the case studies in the data analysis section in Chapter 8 of this thesis.

Just as the literature is limited, the number of construction related LCC case studies is reduced further for those based on the focus of this study, which is the use of timber as an alternative to heavy materials. Access to specific details can be challenging, particularly with private companies' innovative construction solutions due to firms trying to protect their intellectual property. The use of structurally engineered timber in commercial, public buildings and residential projects is a recent undertaking and so there are a limited number of opportunities to review LCC studies (Holmes 2010). A few non-residential and residential examples will be discussed briefly in this section. The reason for including non-residential buildings in this review is due to the lack of LCC of residential case studies. The first LCC was conducted by Page in 2006 and compared a gymnasium and outpatient project in New Zealand on a cradle to grave basis over a 50-year life cycle. The results showed that timber structured buildings were cheaper than both steel and concrete options (Page 2006).

Another case study, by a timber manufacturing company, found timber to be 9% cheaper when compared to steel in an industrial building scenario although there was a lack of detail in pricing and pricing was carried out by two different parties, one an estimator and the other a timber fabricator (Holmes 2010). A third case study found that a timber structured university building had 6% higher costs than the concrete and steel designs with most of this being due to the high cost of laminated veneer lumber compared to concrete and steel (Crews et al. in 2010). A follow up study of this post tensioned frame and sheer wall building with prefabricated timber concrete composite floor system revealed that it was only 3.3% greater than the steel option and 4.6% more than reinforced concrete (Wong 2010). Current cost comparisons in non-residential buildings show some discrepancies both in the scope and results of timber buildings and, as more LCC studies of timber-structured projects are completed, a clearer understanding of LCC between timber and heavy materials will become available (Cabeza et al. 2014).

In larger structural timber residential unit construction there is limited information on the initial construction costing, ongoing performance, maintenance and deconstruction and with only one completed in Australia it may be some time until this will be available. However, a report released this year on a timber redesigned eight-storey apartment compared to a typical reinforced concrete building revealed a 2.2% cost saving for the timber structure (Dunn 2015). Some LCC timber comparative case studies based on detached residential properties in New Zealand and Australia have shown costs based on a mix of initial costs, maintenance and ongoing operating costs. In 2004 Mithraratne and Vale completed a partial LCC comparison of three houses based on a lightweight timber floor and wall frame with cement cladding and compared this with a design that replaced the timber floor structure with 150mm reinforced concrete and a second alternative that had 200mm insulation in the walls and floors as well as double glazed windows. The life cycle costs of construction and operating energy showed the lightweight design costing 917NZ$/m^2 and the concrete and super insulated building costing 11.3%/m^2 and 14.4%/m^2 more respectively (Mithraratne & Vale 2004). It is worth noting that the analysis was carried out over 100 years whereas the majority of recent LCCs use the 50-year analysis period and maintenance and that demolition was not included (Mithraratne & Vale 2004; Cabeza et al. 2014).

Another cost study compared the construction costs of thermally equivalent, materially different house types by an Australian estimating company. The base design house in the study (Type b) was 202m^2 floor area (including the garage) and used the typical concrete floor, timber wall frames with brick veneer and timber roof structure with concrete tiles/metal deck on the garage, whereas the comparative case study homes had the following envelope materials (Davis Langdon 2010):

- Type a – Brick veneer, timber wall frame, elevated timber floor with concrete tile roof on the home/metal deck roof on the garage
- Type b – Brick veneer, timber wall frame, concrete slab with concrete tile roof on the home/metal deck roof on the garage
- Type c – Brick veneer steel wall frame, elevated floor with concrete tile roof on the home/metal deck roof on the garage
- Type d – Brick veneer steel wall frame, concrete slab with concrete tile roof on the home/metal deck roof on the garage
- Type e – Weatherboard clad, timber wall frame, elevated timber floor with concrete tile roof on the home/metal deck roof on the garage

Results showed that the typical volume home with concrete floor and timber framed brick veneer walls was the cheapest (Type b) followed by Type d (+1.9%), Type a (+3.9%), Type e (+4.7%) (that is, the timber maximised house) and lastly Type c (+10.2%) (Davis Langdon 2010). The comparison is upfront costs only and based on the fact that the designs allow for the same operating energy due to equivalent thermal ratings. The costing's also don't take into account maintenance and end of life demolition costs.

Islam et al. (2014) recently completed an LCC of a 101m^2 floor area Brisbane townhouse with a concrete floor and timber framed fibre cement clad wall envelope. They compared this base design with a variety of different wall assemblages that included a timber framed aerated concrete wall, timber framed brick veneer wall, timber frame with pine saw log cladding, and a weatherboard clad timber frame assemblage (Islam et al. 2014). The research included construction, operational expenses, maintenance and end of life disposal based on a 50-year life cycle. LCC revealed that the fibre cement clad design was cheapest at $209,000 with the weatherboard close at 1% extra. The brick and aerated concrete homes were more expensive by 2.3% and 3.8% respectively. The most expensive was the pine log house estimated at 16.2% more than the base case although it was rated at a higher thermal level with 3.7 stars compared to the other designs on 3.6. The study excluded land costs, service installation and internal fit out (Islam et al. 2014).

A lot of variety in LCC comparisons between optimised timber and traditional heavy material buildings is reported in the case studies. Differences ranged between 14% cheaper for timber to 6% more expensive for timber when compared to heavy materials. There were too few cases studies and too many exclusions and variables to draw a convincing conclusion regarding the performance of timber in LCC comparisons with heavy building materials. Further research is required to establish the cost performance of timber in residential construction.

4.4 Time in construction projects

This section discusses time, which is one of the main performance factors in successful projects and was briefly introduced in Chapter 2.5. The importance of time related to general projects, construction projects, and sustainable construction projects and the use of timber will also be reviewed.

Successful projects are considered to have achieved the time, cost and quality parameters set out at the beginning of the project and these success factors apply for both large and small construction projects (Winch, Usmani & Edkins 1998; Chua et al. 1999; Liao et al. 2011). Failure to meet project time expectations often leads to dissatisfaction on the part of the purchaser of the product, which in the context of this research is a place of new residential accommodation (Larson & Gray 2011). Construction time has been considered as one of the most important performance criteria in construction project success in the last three decades and the construction phase has the most issues with time delays when compared to preconstruction phases (Frimpong et al. 2003; Chan & Chan 2004). The construction phase has been defined by Chan & Chan (2004) as the commencement of foundation works to the completion date on the contract.

Time and cost delays are common performance problems in construction projects and these delays have been reported to be increasing, causing issues with cost blowouts and project handover dates (Meng 2012; Ramanathan et al. 2012). The cause of delay of construction projects can include the performance of contracted parties, material and human resource availability, other influential stakeholders performance and environmental conditions (Assaf 2006). Older studies found design changes, labour productivity, planning, and contractor management were significant contributors to poor time control on construction project performance (Frimpong 2003). A recent review of 41 international studies completed between 1995 and 2007 by Ramanathan et al. (2012) has amalgamated the causes of time delays into 18 groups and identified the top 5 factors. These 5 factors in order of highest ranking down to fifth ranking are client changes, contractor delays, design issues and plant/equipment (equal third), labour resources, and finally contractual relationships (Ramanathan et al. 2012).

A more recent contributor to time challenges requiring consideration in construction projects is the growth of sustainability requirements that are either voluntary or legislative (Hwang & Ng 2012). It is well known that sustainable materials and design for construction projects can cause project premiums of up to 25% although less consideration has been given to the factors causing time delays in sustainable building projects (Tagaze & Wilson 2004; Hwang & Tan 2010; Zhang et al. 2011). These have been recorded as being related to design complications, extended and complex approval processes, and unfamiliar construction processes for subcontractors (Eisenberg 2002; Tagaze & Wilson 2004; Hwang & Tan 2010; Zhang et al. 2011). Hwang and Ng (2012) conducted surveys and interviews with construction professionals and reported the challenges in implementing a sustainable building project. Data results from this investigation revealed the main factors affecting time were pre-approval processes, lack of experienced subcontractors, unfamiliarity with green materials and equipment, resistance to change, and unforeseen circumstances (Hwang & Ng 2012).

The reason that time in construction projects is receiving more attention is the effect that delays can have on cost and the perception of clients that the project is successful (particularly in large or extended time scale projects). Speed of construction and site efficiencies were the focus of a number of studies during the late 1900s and early 2000s

(Liao et al. 2011). Algorithms, mathematical modelling and other programming solutions have been proposed in an attempt to produce time reductions on site and some of these are shown in Table 4.4.

Table 4.4 Time efficiency studies for medium/large construction sites

Construction activity	Time objective	Study author/s
Cut and fill excavation	Reduce excavation travel time	Henderson et al. (2003)
Site layout	Minimise personnel travel	Li & Love (1998)
Crane location	Optimise structural concrete delivery to install position	Tam, Tong & Chan (2001)
Floor level material layout	Reduce worker congestion/ increase time efficiency	Jang, Lee & Choi (2007)
Site vehicle movement	Time reduction/increased safety	Soltani et al. (2002)
Concrete delivery to site	Reduce site waiting time	Ferg & Wu (2006)
Equipment selection	Reduce time of equipment use and therefore cost	Haider et al. (1999) Marzouk & Moselhi (2003)

Source: Liao et al. 2011

In addition to the studies mentioned in Table 4.4 that focus on site efficiencies, other studies look at contract and supply chain relationships to reduce delays on construction projects. Skitmore and Ng (2003) analysed 93 Australian construction projects and found that negotiated tender and design and construct contracts reduced project time when compared to projects using either open tendering or lump sum contracts. Meng (2012) employed a survey and interview methodology to investigate supply chain relationships in the UK construction industry and discovered that time delays can be reduced through project partnering with consultants, material suppliers and subcontractors by improving communication, having clear risk allocation and avoiding a blame culture.

In addition to these general studies of construction projects, a number of studies specifically include residential multi-residential construction and the performance measure of time in their research although smaller projects such as detached housing have not been researched to the same extent. (Blyth et al. 1995; Vines 2000; Ng et al. 2001). This may be due to the management of these projects being more centrally focused rather than site based so that less attention is given to site operations and its associated efficiencies (Foresythe, Davidson & Phua 2010). A comparative study by Clarke and Herrman (2004) of over 300 housing units (homes, townhouses and units) in Scotland, Denmark, Germany and England looked at productivity and cost and found that speed of construction was significantly slower in England compared to the other three countries. This was attributed to factors like less prefabrication and upfront design, lower skilled labour force, reduced use of technology and machinery, and the method and form of construction in the case of England's building industry (Clarke & Herman 2004). The Danish had the highest level of prefabrication and management, shortest completion times and lowest work force in the projects studied (Clarke & Herman 2004).

An Australian study in 2010 by Foresythe, Davidson and Phua of 195 homes attempted to link gross floor area (GFA) and the number of levels (NoL) with both the estimated and actual time of construction of detached homes in addition to trying to ascertain if cost overruns determine extensions of project time. Results demonstrated a strong correlation of GFA to estimated project time and a weaker correlation to NoL but the GFA had a weak correlation to actual construction time and there was a slight negative correlation to NoL and actual time of construction (Foresythe, Davidson & Phua 2010). The study also found that cost increases determined time overruns more often in the larger homes than smaller ones with the main determining factors being unforeseen site factors, site management errors and site workmanship issues. Design changes and preconstruction errors had less impact on time (Foresythe, Davidson & Phua 2010).

It has been suggested that the use of timber provides time, cost and quality benefits during construction providing current issues with timber can be overcome. (Bayne & Taylor 2006). Holmes (2013) investigated a few innovative uses of timber systems in new building projects and discovered that there were delays to the estimated schedule in the design stage, fabrication, delivery and erection of buildings constructed with structural timber systems. Comparatively, multi-residential projects using CLT have realised time reductions during erection with London's Murray Grove building saving 23 weeks off the erection time and Lend Lease's ten-storey building in Australia taking 30-40% less time for the structural system compared to concrete (Crossin 2012). Australand's estimating manager reported that the 12-month construction schedule for their innovative timber cassette residential apartment building provided a one-month advantage over conventional methods using reinforced concrete (Jong 2014). These case studies of recently completed residential projects using timber as the main structural element suggest that timber could provide a time saving benefit during the construction stage of residential development projects.

This section has discussed time as one of the main performance indicators for both large and small residential building projects and reported some of the contributing factors to project delays. These delays can be caused by the performance of clients, consultants, suppliers and subcontractors, as well as site and contract managers, errors in time estimates, schedule control and resource procurement. Sustainable projects are noted as causing delays related to lack of familiarity by consultants and contractors with sustainable methodologies, approval processes and learning curves associated with new material systems. A number of studies discussed looked at increasing the efficiencies of material and labour movement around larger construction sites and documented the use of timber systems as a solution to residential construction time constraints. The following section discusses thermal performance of residential construction and the use of AccuRate as the approved thermal modelling program used for the energy rating requirements of Australia's building code.

4.5 Thermal performance in residential construction

Thermal performance of residential properties is influenced by many different factors and these include minimum legislative performance, material selection, local climate, surrounding physical environment, quality of construction, and building orientation. Other factors affecting the internal thermal environment include access and use of natural lighting and ventilation, occupant behaviour and available cooling and heating devices. Multi-residential properties are required to comply with legislation that affect a structure's thermal performance as well as minimum fire and acoustic performance. These influence the type and thickness of materials for separating floors and walls between apartments and between apartments and common areas (BCA 2013). This section will focus on the perception of occupants about thermal performance in detached homes, building code requirements on thermal performance in residential construction, the use of the thermal modelling tool AccuRate for homes, and some of the existing research using the simulation tool in Australia.

4.5.1 Perception of thermal performance of housing

Complaints and dissatisfaction about buildings' thermal performance are commonplace in buildings of many classes despite the advances of technology in controlling the thermal comfort of internal building spaces (Nicol, Humphreys & Roaf 2012). International standards provide guidelines of appropriate indoor temperatures based on the type and building, occupancy and building usage (ASHRAE 2004 & 2009). Subjective temperatures experienced by building occupants can be influenced by a range of variants including air temperature, humidity, air flow, radiant heat, individual metabolism, physical activity and clothing (Moss 2008). Despite the internationally adopted definition of thermal comfort being "the state of mind that is satisfied with its thermal environment", a person's perception of thermal comfort can be based on previous experience or expectations of a current experience (ASHRAE 1966; Parsons 2010). Whilst the thermal climate of some buildings is out of direct control of the occupants or visitors, such as in commercial buildings, shopping centres and public buildings, residential buildings are controlled by the occupants and they will engage the available variety of passive and active heating and cooling methods in an attempt to maintain satisfactory thermal comfort levels (Aldawi et al. 2012). A study of 233 low to middle income residential occupants in South Australia was conducted to measure responses to temperatures between 21°C and 34°C and found that windows were utilised at 25°C, fans at 27°C but air conditioning not until 28°C (Soebarto & Bennetts 2014). The study recommended that to reduce operating energy related to heating better designs should be employed for both environmental and cost reasons (Soebarto & Bennetts 2014). High thermal efficiency of new residential building envelopes in Australia was also a key recommendation from a study by Morrissey and Horne in 2011. They also suggest that our legislative building standards for thermal performance are weak when compared with international standards (Morrissey & Horne 2011).

Building code thermal performance for new multi-residential housing is dictated by Section J (Energy efficiency) of the Building Code of Australia (BCA), the objective of which is to reduce greenhouse gas emissions through the efficient design and construction of new buildings and their services (BCA 2013). Minimum requirements set out in the BCA (2013) include some of the following measures:

- Minimum thermal values for materials used in the envelope to resist thermal transfer into the building (R-value)
- Sealing of the building envelope to minimise heat exchange
- Maximise the use of air movement for heating and cooling efficiency
- Minimum shading of walls to reduce cooling loads in summer

Detached dwellings also have minimum legislative thermal performance requirements that are not dissimilar to those for multi-residential buildings. To conform to building code standards for acceptable construction a dwelling needs to have a maximum conduction of heat from all glazing, minimum thermal resistance of envelope materials, conforming installation of insulation materials, sealing of the building envelope to avoid infiltration, and shading of glazing and wall elements (BCA 2013). There is another option for compliance that involves using approved house energy rating software. A minimum star rating of 6 is required for all homes except those in Climate zones 1 and 2 (north east coast and coast at top of Australia) and which have an outdoor living room with impervious roof (BCA 2013).

The current approved thermal simulation software for residential development is based on the calculation engine Chenath, and the software options for user interface include AccuRate, BERS professional and FirstRate (NatHERS 2014). These thermal simulation tools are used in determining house thermal performance in Australia and provide a star rating for comparison and benchmarking and a predictive heating and cooling load per square metre of conditioned space (Dewsbury 2011). The programs account for the varying climate zones in Australia and calculate simulation based on house orientation, envelope systems, insulation, glazing, wall shading, and the natural ventilation potential of openings (Dewsbury 2011). These energy simulation programs have been tested against international reference programs and found to have performed satisfactorily to the international standard ANSI/ASHRAE 140-2001 (Delsante 2004; NatHERS 2014).

The next section will focus on investigations in the literature on a thermal simulation program commonly used in Australia. The justification for the focus on AccuRate in particular includes the following reasons:

- It adheres to the Building code of Australia alternate solution for thermal performance
- It has been used in recent a number Australian housing thermal studies
- It was developed, tested and approved by the Commonwealth Scientific Investigation Research Organisation (CSIRO)

Research completed by Soebarto and Bennets (2014) demonstrated that AccuRate simulations accurately reflected conditions in unoccupied test cells although there were anomalies when tested against occupied brick veneer and low energy homes. A survey of 170 households in the same study indicated that the use of heating and cooling by occupants did not match AccuRate's assumptions of simulation and energy costs, and probably supplies the reason for these anomalies (Soebarto & Bennets 2014). Typical occupant energy use behaviour for heating and cooling and behavioural changes associated with energy prices and changing lifestyles, it has been acknowledged, do not accurately reflect assumptions within thermal simulations (Soebarto & Bennets 2014). So whilst thermal simulation programs can predict home thermal performance they do not address occupant usage. This problem is outside the scope of this thesis and so will not be addressed in any depth.

Despite the issues of occupant usage, AccuRate has been used in a number of recent LCA studies as the basis for estimating operating energy. An LCA of typical Australian brick veneer homes compared to alternate wall and floor systems of timber and steel use the AccuRate simulation in order to redesign alternatives in order to compare homes on an equal thermal basis (Carre 2011). Equal thermal rated designs were created in order to provide the LCA comparison based on equal parameters for operational energy (heating and cooling). Aldawi et al. (2012) compared the conventional house brick veneer wall system to an insulated rendered concrete wall envelope using AccuRate in six Australian cities representing different climate zones. The results showed that the concrete system reduced cooling and heating by between 14% and 33% (Aldawi et al.

2012). Islam et al. (2014) compared wall assemblies constructed of timber, aerated concrete, brick, and fibre cement using AccuRate to determine heating and cooling loads during the operational stage as part of a LCA/LCC study. The research demonstrated that an increase in thermal performance correlated to a reduced operational energy load and life cycle cost and over the life cycle of 50 years the timber home outperformed the brick and aerated concrete home for both energy and cost (Islam et al. 2014).

This section has reviewed the perception of thermal performance for residential building occupants and found that computer generated simulations don't always predict accurately the behaviours and experience related to the thermal comfort of occupants. This section also provided an overview of the Australian building legislation requirements for energy performance and thermal simulation programs. The accredited program AccuRate is commonly used for detached house simulations and is also the subject of a number research articles. It has been used to assist in the redesign of building envelopes for thermal comparison and has also been used to compare building envelope performance for heating and cooling for existing heavy material. There has been limited research, however, into thermal performance of building envelopes comparing heavy materials and lightweight materials.

4.6 Conclusion

This chapter aimed to investigate the current situation of sustainability in residential development by investigating the performance indicators that are part of the paradigm for sustainable construction. LCA, LCC, construction time and thermal performance were particularly investigated for the Australian context. The literature revealed quite a number of international studies addressing these performance measures while local studies were limited in either number or scope so their comparisons of the performance of heavy materials relative to timber are limited to individual scenarios. The following chapter provides an overview of the method of investigation in the Australian context for the performance of timber versus traditional heavy materials. The investigation includes a questionnaire survey of home occupants and interviews of construction practitioners and focuses on their perceptions of the performance of timber regarding sustainability, cost, time and thermal adequacy. The results from the data collection in this stage will be used to inform the basis for conducting case studies later in the research.

Chapter 5 Research Method

5.1 Introduction

The research in this thesis aims to develop a residential development model to increase the sustainability of residential construction projects through the increased use of timber and engineered timber products. The use of timber and traditional materials is viewed and compared from a life cycle perspective and the carbon impacts caused throughout the cycle starting from their procurement to their disposal/recycling. Through a questionnaire survey and interviews a model will be developed to overcome existing barriers and take advantage of opportunities for increased timber usage in residential development in Australia. Case studies will be used to test the model according to the specific performance criteria.

This chapter covers the methodology options available and the methodology chosen to fulfil the aims of the research goals. Even though the research uses a survey to collect part of the data, the methodology is primarily qualitative. The chapter will also discuss the choice of case study methodology and its relevance to the research. The data collection method used, including survey and interviews, will be looked at as will the research strategy and interpretive epistemology supporting my qualitative research.

5.2 Methodology options

Four research strategies have been suggested by Bell (1993) to include action, ethnographic, survey and case study. Yin (2009) describes five research strategies commonly used in social sciences – experiment, survey, archival analysis, histories and case studies. All these strategies are briefly summarised below (Fellows & Liu 2008; Yin 2009):

- *Action research* – involves the researcher to actively participate in the process under study in order to identify problems and produce solutions

- *Ethnography* – studies races and cultures and requires passive observation of a particular groups actions, conversations to in an attempt to understand reasoning's for patterns of behaviour
- *Experimental* – best suited for problems in which variables are known or hypothesised with high level of confidence and in which the researcher can directly influence events
- *Survey* – used when research is focused on documenting a particular prevalence of a particular phenomena
- *Archival* – is the use of records held in archive as the source of data
- *History* – involves the use of data collection from primary and secondary documents
- *Case study* – a thorough investigation of specific instances in the area of research undertaken by the researcher

The application of strategies proposed by Yin (2009) depends upon the type of research question, the level of control the researcher has over behavioural events, and whether events are current or historical. Table 5.1 shows the criteria for choosing five common research strategies (Yin 2009).

Table 5.1 Requirements for different research strategies

Strategy	Form of research questions	Requires control of behavioural events?	Focuses on contemporary events?
Experiment	How, why?	Yes	Yes
Survey	Who, what, where, how many, how much?	No	Yes
Archival analysis	Who, what, when, how many, how much?	No	Yes/No
History	How, why?	No	No
Case Study	How, why?	No	Yes

Source: Yin 2009

As discussed at Chapter 1.1, this research is concerned with looking at contemporary events, it requires no control over the event and the research proposes 'how' and 'why' questions. How and why questions fit three of the types of research methodologies identified in Table 5.1, history, experimental and case study. History is not a suitable methodology here, as it does not focus on contemporary events. Experimental is both suitable for contemporary events and how and why questions although it requires behavioural control over the events and this is not applicable to this research. Case study was chosen as it fits the criteria of the type of research question, contemporary relevance and the lack of control over the behavioural event.

A number of studies have used data collection methods to study the perception, barriers and opportunities of timber use in construction through the use of qualitative research. These incorporate the use of data collection strategies that include interview, survey or a combination of both. These studies have investigated perceptions and decisions of consumers, designers, construction practitioners and product suppliers in the construction industry. Damery and Fisette (2001) surveyed architects to find their motivating factors for material specification in residential construction. Qualitative studies were used by the European Commission (2002) to establish public perceptions on the sustainability of timber use and forestry practices in the United Kingdom and the Netherlands. The Building Research Establishment (2004) used a questionnaire survey of construction practitioners in Europe to identify legislative barriers to timber use in the European Union. Consumer preferences for timber products have been investigated using interviews by Roos and Hugosson (2008). More recently, Macias and Knowles (2011) used mail and online questionnaires to determine the reasons for designers' specifying timber flooring and Schmidt and Griffin (2013) used survey and semi-structured interviews to gauge the opinions of practitioners about the barriers to engineered timber use in multi-family housing in Portland, Oregon.

Bayne and Page (2006) used a case study methodology applied to the Australian construction industry to establish the attitudes of construction designers towards timber in major building projects using focus groups and interviews. Nolan (2009) used a mix of quantitative and qualitative (questionnaire and survey) collection techniques to explore the potential for increased use of timber in all construction types in Australia from an industry perspective. These studies support the use of case study methodology in this research to study perspectives, barriers and opportunities of timber use in the residential development sector. These studies guided the decision to use case study methodology using both quantitative and qualitative data collection methods due to the combined technical elements and perception of materials in residential construction. A purely technical approach that focused on design, structure and performance would fail to capture the human element in the decisions from both supply and demand side. Perception from the supply side of building materials influences preference for certain types of construction methods. The demand side also uses perception and experience to make decisions between materials chosen for a significant life purchase. It was therefore considered important use methods to capture both supply and demand side perspectives in addition to technical and emotive data through a variety of data collection techniques. The following section compares the use of quantitative and qualitative methods of research in addition to briefly looking at the validity of mixed methods and the chosen method for this study.

5.3 Qualitative vs. Quantitative Research

Quantitative research is motivated by numerical outputs and quantification of events or characteristics of people (Thomas 2003). Quantitative researchers usually adopt a positivist philosophy and therefore seek to collect factual data and study how the outputs relate to previous findings in the literature (Fellows & Liu 2008). Quantitative research designs are predominantly fixed, structured and set up to ensure accuracy in measurement and classification (Kumar 2011). Some of the common methods in quantitative research include surveys, laboratory experiments, econometrics and mathematical modelling (Myers & Avison 2002). One distinguishing feature of quantitative research is that the detail included in the design allows for replicable results if given the same circumstances (Kumar 2011).

Qualitative research often deals with people, groups and events that cannot always be quantified and therefore a different approach is used to understand these phenomena within the social or cultural context in which they exist (Myers & Avison 2002). The focus is therefore based on gaining understanding, explaining, discovering and exploring situations and events, as well as interpreting perceptions, beliefs, behaviours and actions of individuals and groups of people (Kumar 2011). This research method is associated with relativist or interpretive paradigms and has been criticised by the scientific/positivist community claiming that the objectivity of data is questionable (Taylor 2000; Fellows & Liu 2008). The other main criticism of this method is the difficulty in reproducing its results given the variable nature of phenomena and its subjects of study or observation (Kumar 2011). This perceived weakness is also the reason that quantitative methods are unsuitable for data collection and analysis, involving as they do the variability and lack of control present in phenomena and events that rely upon people's perceptions, decisions and interactions. Qualitative data collection methods often include the study of particular cases, personal experience, interview, researcher participation and observation (Taylor 2000; Denzin & Lincoln 2000).

The multiple strategy approach to research combines both quantitative and qualitative methods. When viewed from a purely epistemological perspective, the joining of these two methods is not possible although most researchers take the technical perspective in which the research method from one strategy can be utilised in the other method (Bryman 2004). Hammersley (1996) classified multi-research strategy into three approaches named triangulation, facilitation and complementarity. These are described in the following points:

- *Triangulation* uses quantitative research and qualitative research to confirm the others findings
- *Facilitation* uses one strategy to assist the other research strategy
- *Complementarity* is the use of both strategies to combine different aspects of the investigation.

5.4 Data Collection Methods

5.4.1 Questionnaire Surveys

A few options were available to distribute questionnaires including personally administered, by mail and by Internet. Personally administered questionnaires are often used in a local area or within organisations and have the advantage of the researcher being able to explain the topic, answer queries and arrange for collection personally or through return post (Sekaran 2000). Postal questionnaires are sent via the post often with a return address, pre-paid envelope for the response return or a drop box if administered within a firm or organisation (Bryman 2008). Mail questionnaires have benefits to the respondent of being able to complete questions at their own convenience and, when combined with advance warning of the survey and follow up letters, can elicit reasonable response rates (Sekaran 2000). Some disadvantages of these two self-completion questionnaires include challenges of time consuming distribution and completion, slow response rates in the case of the mail questionnaire. The questionnaire recipient may not understand the content due to language or educational limitations (De Vaus 1996). There is also the issue of the labour intensive analysis of collected data on written questionnaires. The Internet seemed an effective way to overcome some of these issues and so was used to distribute the questionnaires.

5.4.2 Internet questionnaire

Distributing questionnaires via the Internet reduces the time and cost in producing, distributing and formatting questionnaires and in analysing the data received in the responses (Hewson et al. 2003). Some disadvantages noted by Sekaran (2000) of this distribution and collection method are the requirement of the participants to be willing, computer literate and have access to a computer. Moreover, the sampling technique may not be random and it will be difficult to ascertain the response rate in relation to the population size. Hewson et al. (2003) even suggest that bias can occur through random web surveys due to 'volunteer effect' factors and 'frequent user' effects and recommend that user groups and individual contact be used to reduce this bias and maintain greater researcher control.

5.4.3 Interviews

A number of interview methods were available to the researcher and these include group interviews, internet or telephone interviews, or face-to-face interviews, either structured, unstructured or semi-structured. Structured interviews are often used in qualitative research so as to increase the validity and reliability of key concepts, and gain responses to a clear set of specified questions under investigation with less emphasis on the interviewee's own perspectives (Bryman 2008). This method was deemed inappropriate as the research relied on the opinion and perspective of the participants to broaden the discussion of initial issues identified by the researcher.

Group interviews can be conducted in both formal and informal settings and can be unstructured, semi-structured or structured. Their advantages over individual interviews are in relation to reducing both time and cost in addition to producing rich data whilst being stimulating for participants. The disadvantages include the possibility that a dominant person/persons, or group culture, can interfere with individual expression and it is difficult to discuss sensitive topics (Fontana & Frey 2000). The sensitive commercial information under discussion, the challenge of arranging a simultaneous meeting of senior construction professionals who work for competing companies, and the lack of experience of the researcher to conduct group interviews are the mains reasons for not using this method.

Telephone interviews can be an efficient method of collecting data and have been used in market research and academic data collection (Berg 2009). The method can help to create a relaxed and informal meeting for the interview to encourage the sharing of personal experience and reflection on the research topic. A telephone interview would not allow the interpretation of facial expressions and cues and could also allow the participant to be engaged in work activities or other distractions so phone interviews were rejected as a data collection method.

Internet interviews, like telephone interviews, are also known for their time and cost efficiency as well as having broad access to a large audience (Hewson et al. 2003). Internet interviews do not allow the same chance for building a rapport with the interviewer and require more effort from the interviewee to maintain engagement (Curasi 2001). Curasi (2001) also found that, although Internet interviews tend to be more considered and punctually correct, less information is often provided compared to face-to-face interviews and the interviewer has less impact on the direction of the interview. For reasons of rapport difficulties and lack of interviewer control, the Internet interview was not employed in this research.

Semi-structured face-to-face interviews are based on a loosely defined set of questions or line of inquiry produced by the researcher which allows the interviewee to elaborate and change the direction of the conversation under the guidance of the interviewer (Bryman 2008; Silverman 2010). This type of data collection allows fluidity in successive interviews as the discussions from earlier interviews are permitted to alter the line of enquiry for the latter interviews (Beardswearth & Keil 1997). Qualitative interviews also allow for improvisation on the part of the researcher to explore particular issues in more depth or change tack in the middle of an interview (Janesick 1998). Other reasons for employing this data collection method particular to the research and researcher are listed below:

- Some interviews would contain discussion of confidential proprietary information and the researcher wanted to confirm at the time of the interview what information would be able to be used and following interview discussions
- Rapport between the interviewer and interviewee was one of the desired outcomes not just for the current research but also for future study and industry contact
- The researcher had experience in face-to-face interviews in previous employment and wanted to exploit that skill to benefit the data collection process

Face-to-face interactions enable one person to participate in the mind of another and take the role of the other to obtain social knowledge (Lofland & Lofland 1995). These also allow the researcher to view things from a perspective that an outsider may not be able to view (Bryman 2008). This is vital for this study as the perception of participants can represent the opinions of those who are critical in embracing the construction innovation that is the focus of this part of the study. Alongside the benefits of rapport and open discussions and topic exploration in semi-structured interviewing can be found some criticisms and other issues. These include the lack of objectivity in the line of questioning, difficulty in replication of findings from qualitative interviews, and interviewer bias.

Subjectivity is an issue faced by those conducting interviews that start broadly and narrow down to specific questions based upon the interviewer's preference rather than any clearly defined objective goals (Bryman 2008). The objective purpose of the interviews in this research was to discover the opportunities and challenges of increased timber product use in residential development. Considering that there is no precedent in this type of construction in medium-rise residential projects and limited timber use in new homes, it was inevitable that the direction of the interviews would be exploratory and the opinions sought would be subjective to interviewees' individual construction experience and personal preferences. The researcher encouraged the exploratory nature of the interviews in an attempt to capture a broad range of issues that could be investigated in further detail through the data analysis.

The difficulty in replicating results from interviews is another criticism directed at qualitative research (Bryman 2008). A number of factors could contribute to this including:

- The context in which interviews take place
- The influence and bias of the interviewer
- Lack of structure around the interview process
- Personality of respondents

The replication of interview findings results was not seen as a major issue due to the speculative and opinion based nature of the initial enquiry into the increased use of timber in residential development.

The interviewer will always bring a certain degree of bias to the interviews depending on their background, training and personal perspectives on the study (Guba & Lincoln 1998). Some literature suggests that bias should be avoided and interviewers should take a neutral stance in the data collection process (Brennar, Brown & Canter 1985). Other authors accept bias as a part of the interview process and all the subconscious influence that an interviewer brings to the interview allows for the data collection to be a co-constructed with the participant (Finlay 2002). Clawson (2011) recommends that the researcher should neither abandon their bias nor make them the driving force of the interview process but should allow themselves to be changed through the interactions. A number of biases that the researcher of this study could bring to the interviews are listed below:

- A history of working with timber.
- Preference for the use of timber in construction over heavier materials.
- The desire to see a more efficient construction methodology over current methods.
- A keen personal interest in the preservation of natural resources and a perception that timber may be one of the key solutions.

In an attempt to reduce the impact of researcher bias towards timber on the interviews, the initial questions in the interview scheduled for the pilot interviews were closely based on the literature review and from there were permitted to develop from the participants' experience. In addition the questions were weighted towards the barriers to the introduction of timber medium-rise construction whereas the advantages were explored within open discussion with participants. It is acknowledged that there was a specific line of questioning in an attempt to ascertain or at least explore the feasibility of increasing timber use in residential developments from a sustainability, cost, time and quality perspective.

5.3.4 Pilot interviews

Pilot studies can be used in qualitative research to assist in developing and refining data collection methods (Forsythe 2003). Silverman (2011) encourages pilot interviews not only to try out different types of questioning but also to provide the novice with interview practice prior to the remaining interviews. There were a few reasons why a small pilot study was important prior to the bulk of the semi-structured interviews.

1. The interview questions were derived from a general body of literature regarding timber construction and questionnaire survey results and did not represent the perceptions of Australian construction practitioners. Pilot studies

would help eliminate information not relevant to the Australian construction industry.

2. Interviews would be carried out with a variety of specialty consultants in the construction industry so the pilot could assist in identifying specific issue areas that had not been contemplated by the researcher.
3. The pilot study allowed the interviewer to become accustomed to the length of the interviews and practice guiding the process for the purpose of productivity.

5.4 Research Design

Even though this research is essentially qualitative, it implements the facilitation approach to multi-strategy research by using the data results collected from questionnaire surveys to homeowners to guide the second part of the study. The second part of the study is aimed at suppliers of residential developments and involves semi-structured interviews with construction practitioners. Results from both the surveys and interviews are used to develop a strategic model to increase the use of sustainable materials in residential development and reduce carbon emissions through timber use over the material cycle for housing in Australia. Comparative case studies are used to evaluate sustainability, time, cost and thermal performance of the strategic model. Despite surveys being associated with quantitative methods, the questionnaire in this study will focus on the perceptions and experience of participants and compares and contrasts two different groups' responses, namely, home owners and construction practitioners. The semi-structured interviews are exploratory and based around the perception of construction practitioners within the context of their skill, experience and work practice. Both these data collection strategies are interpretive and more often associated with qualitative research (Kumar 2011). The comparative case studies will use costing and program documentation from building case studies and analyse numerical data.

The research includes two stages of data collection, questionnaire survey and semi-structured interviews. The questionnaire focused on participants' perceptions and experience of time, cost, sustainability, and (quality) thermal performance of timber and engineered timber in residential developments. A comparison between homeowner participants was also conducted in an attempt to establish if there was a difference between the perception of homeowners with a background of construction experience and those with no construction experience. The second stage investigated the major barriers to and benefits of increasing the use of timber products in residential developments in Australia. Semi-structured interviews were the data collection method in the second stage of data collection.

Quantitative data collection methods were deemed the appropriate means to meet the aims of stage one of the study for a number of reasons:

- The ability to objectively distinguish particular differences between the views and life situations of participants (Silverman 2000)
- The capacity to compare two different occupation groups within a population based on a consistent measure
- The utility of producing a reasonably accurate measurement of relationships between different concepts (Bryman 2008)
- The practicality of using a tool similar to previous studies in relevant research. This will enable the results of this study to compare and document the sentiment of homeowners towards timber as a building material in different countries over time

A number of criticisms of quantitative research can be applied to this research. The first is the positivist approach of applying an exact science to an inexact social scenario which contains innumerable influences on its relationships and decision making (Bryman 2008). The correlations between variables and meanings derived from these correlations are not scientifically determined but are influenced by the researcher's own objectives and reasoning (Silverman 2000). An additional issue pertinent to this research is whether the participants have the knowledge to answer questions and whether they interpret questions as intended by the researcher (Cicourel 1982). Although not all these criticisms can be refuted, the design of the research can reduce some of the subjective influences of quantitative research.

There are a number of different research designs available for quantitative researchers and the benchmark for high levels of internal validity and confidence in determining causality is often associated with experimental design (Bryman 2008). Laboratory, natural and quasi-experimental design generally involve more than one group of participants in which an experimental group is subjected to a different treatment or experiences (independent variable) from a control group to test whether the focus of measurement (dependant variable) differs between the groups. This is achieved through measurements of the dependant variable before and after the treatment (Sekaran 2003). This type of research design was inappropriate due to the impracticability' and ethical challenges of working with participants' experiences of living in dwellings made of different materials. In addition, no-one was living in structural timber medium-rise apartments at the time of the questionnaire so peoples' opinions and perceptions of building materials for residential properties was deemed the most suitable way to proceed.

Cross-sectional design was considered appropriate due the aims of this part of the study and the practical issues faced through the time constraints of participants. Cross sectional design is interested in variation between multiple cases with data collection being carried out at one time in a format that allows only for the examination of relationships between variables rather than over time or through the manipulation of variables (De Vaus 2001). This research's aims included a comparative analysis between participants who have experience in the construction industry and workers from other industries. For this reason a comparative design using the cross-sectional design format was finally chosen to carry out the research. Due to the considerable sample size of the two different employee groups participating in the study an online questionnaire was used as the data collection instrument.

The questionnaire surveys focus on 'why' or 'why not' homeowners would choose certain materials for housing based on their experience and understanding of timber, brick, and reinforced concrete in the residential setting. Participants are required to provide demographic information such as their particular profession, age, gender, place of residence etc. They also gave their perception about the sustainability aspects of timber and heavy materials, their willingness to pay extra for sustainable materials and their experience and preference for materials based on speed of construction, thermal performance and cost of construction.

Using the responses from stage one and timber performance results from the literature review, stage two data collection was designed to suit semi-structured interviews with Australian construction practitioners. Questioning was based on confirming or disproving the current perception of barriers and benefits of timber use in residential construction and 'why' there is not an increase in in the use of timber products in residential developments. The other main line of questioning was based on 'how' the construction industry the can overcome the barriers and capitalise on the benefits of timber related to the themes of time, cost, quality and sustainability.

5.5 Analysis

There are two common analytical approaches to qualitative research recommended by Gibson and Brown (2009) and these are 'top down' or 'bottom up'. Top down uses an existing theory against which to interpret the data whereas bottom up uses the data to generate themes that lead to a theory and this second method is known as the grounded approach (Glaser & Strauss 1967; Gibson & Brown 2009).

This research takes a constructivist perspective to the application of grounded theory, which is an inductive approach that is quite common in qualitative research (Glaser & Strauss 1967; Charmaz 2000). The constructivist perspective in this research is the study of peoples' perceptions according to their experience and context. A grounded approach in the context of this research is the use of data collected and analysed to develop a theory and is explained in more detail through the ensuing steps (Bryman 2004):

- Questions from literature directed the investigation and initiation of the first stage of data collection and from these results the second stage of research was devised

- The second stage of data collection and analysis produced concepts from a coding process and these were then used to refine the line of questioning for the remaining data collection through semi-structured interviews
- Data collection was continued until the major themes had reached theoretical saturation and there was no new data emerging

Once the interviews produce no new data analysis will commence on the interviews in order to identify the major themes raised. These themes will be used to produce a sustainable residential model as an alternative to the current linear model that uses heavy materials. Case studies will be used to test the sustainable model.

5.6 Case studies – Comparing timber performance against concrete and brick in residential development

The main focus of these case studies was to obtain the following information:

- Cost of building
- Time of construction
- Energy embodied in the materials and processes to build the homes
- Identifying if the size and type of residence affected the criteria under test (time, cost, carbon impact)

The data from the case studies will be used to validate the sustainable residential development model developed from the first two stages of data collection. Data collection will be primarily sourced from documentation provided through personal contacts. Six types of data are commonly used in case studies: documentation, direct observation and participant observations, archival records, interviews, and physical artefacts (Yin 2009). Direct or participation observation wasn't relevant as the projects were recently completed and on most projects it is not practical for observations to be carried out over periods of up to a year. The cases are contemporary, so archival records and the study of physical artefacts is not applicable. Interviews are used in the second stage of the study but not required in the comparative case studies for data collection. Data collection for case studies include project drawings (floor plans and elevations, structural), costs in the form of payment schedules and trade invoices, and contractual schedules. Where documentation is incomplete or comparisons required, the use of industry standard cost, scheduling and thermal analysis tools will be utilised. More detail on the data collection and case selection will be discussed in Chapter 8.

5.7 Ethical considerations

Numerous ethical issues needed to be managed through the planning stage and ethical approval processes. A number of stakeholders to be considered include participants, the researcher and the funding or educational body supporting the research (Kumar 2011). The human contact element associated with qualitative research automatically raises a number of general ethical considerations to the fore and these include the following issues particular to the participants (Silverman 2011):

- Voluntary participation and the right to withdraw.
- Protection of research participants identity.
- Assessment of potential benefits/risks to participants.
- Informed consent.
- Not doing harm.

Due to the fluid nature of conducting semi-structured interviews, there may also be lines of enquiry or responses that may not have been planned at the outset and the interviewer must also be aware to maintain the ethical requirements of the research (Silverman 2011).

The ethical considerations and process for this research will be discussed followed by a description of some of the particular issues that were faced during data collection. The ethical submission included information regarding the data collection method, data storage and security, use of the data and confidentiality. In addition, a sample of the questions to be used in the questionnaire and semi-structured interviews were provided to the university Ethics Committee as well as the contents of the consent form and information sheet which would be given to participants. Other information such as the expected time of interviews and the possible inconveniences placed on interviewees were required in the ethics submission.

The questionnaire was distributed by email and included a description of the research, ethics approval contact details for participants who wanted further information and an option to withdraw from participation at any stage of the research. Details of the security of the data collected and the intended usage of the data were also included in the survey introduction. The questionnaire was anonymous and only those people who wished to be a part of the second stage of data collection were requested to provide contact details. One issue of the questionnaire was encountered when the link to the survey was broken due server issues within the university. Once recognised, an apology email was sent to the particular group affected and they were invited to make a second attempt.

The implementation process of ethical requirements to engage interview participants is outlined below:

1. An introductory email or phone call was made to potential participants, which included a brief explanation of the research and time required for involvement. (This step was bypassed for those who requested to be involved via the online surveys).
2. A time was arranged to meet potential participants at their workplace or the researcher's university. Time commitments were emphasised along with the ethical requirements of the research, which included voluntary participation, confidentiality and the need for interviewees to sign a consent form.
3. In the days prior to the interview a reminder email was sent along with pictures of the construction project typology that would form the basis of the interviews.
4. At the commencement of each interview permission was requested for the use of digital audio recording equipment to assist in interview transcription and consent forms were provided for the participants to sign along with an explanation of the contents of the consent form. An information sheet was also provided to interviewees.

5. At the conclusion of each interview the participants were given a chance to withdraw or withhold any part of the conversation and consent forms were collected.

One of the issues expected in the interviews was the challenge of creating an informal atmosphere that fostered open, free flowing conversation with the formalities of obtaining consent and explaining all the ethical considerations surrounding the interview process (Lykes 1989). This was not the case, however, as most participants seemed indifferent towards the ethical considerations and so deliberate insistence on following the ethics requirements of the research was employed in order to obtain the signed consent forms. Another risk faced by the researcher was the accidental discussion of confidential intellectual property. Interviewees would also discuss small points in their interview derived from their connections/relationships with persons involved in particular construction projects that included new methodologies and techniques using engineered timber products. The researcher was required to be tactful and discrete when directing conversations and be constantly aware of information that was either public or private.

All information was desensitised and details of participants were stored in separate locked locations in secured rooms within the university. Interviews were digitally recorded for accurate transcriptions and security of storage. Transcribed data was imported to and analysed using the computer aided qualitative data analysis software NVivo. An initial coding of minor themes was completed and then compiled under the major themes of sustainability, time, cost and quality. An in-depth analysis of the interviews can be found in Chapter 6.4.5.

All case study documentation was desensitised and all names and addresses were removed from publishable data. This was particularly important with the detailed costing information as it contained information of the developers' costs, supply details and profits. This information was kept in a locked room in a security-patrolled area of the university. Digital data was kept secure in password-protected computer in a locked university room. There were no issues with the ethical process related to the case studies.

5.8 Conclusion

This chapter discusses both quantitative and qualitative research and discusses case study methodology for use in this research. Qualitative research using grounded theory was used to guide the inductive approach to establishing a hypothesis in this study. The hypothesis that timber use in residential development will have performance benefits in time, cost, quality and sustainability when compared to heavy materials such as reinforced concrete and brick materials will be measured using embedded case studies found in Chapter 8. The next chapter will discuss details of data analysis and results of the first two stages of the data collection that is the questionnaire survey and interviews.

Chapter 6 Data Collection & Analysis – Survey and Interview Results

6.1 Introduction

This chapter describes the purpose and methods of collecting data and presents the findings from homeowner surveys and interviews with construction practitioners to identify key issues surrounding and barriers to the replacement of heavy materials with timber in residential construction in Australia. The chapter is separated into two parts to reflect the progressive nature of the data collection process and analysis with survey results used to guide the line of questioning in the interviews.

The first section discusses the results from a survey of Australian homeowners that were used to determine whether negative perceptions of timber found in previous European studies were replicated in Australia in addition to highlighting current views on timber as a sustainable building product. The results from the surveys in addition to the current literature on timber performance formed the basis of the interviews with construction practitioners to establish the key industry barriers in Australia to increased timber use. Both sections of this chapter discuss separately the purpose, process, sampling, results and limitations of the data collection method and analysis. The conclusion summarises the results and introduces their purpose in developing a strategy for increasing timber in Australian residential developments to be discussed in depth in Chapter 7.

6.2 Questionnaire survey

6.2.1 Survey purpose

The purpose of the questionnaire survey is to establish the current perception of homeowners and occupants in Australia on the increase use of timber in residential construction of timber in lieu of heavy materials. An online questionnaire is used to help meet the following objectives:

1) Understand the demand side of the residential construction market, in particular the exploration of owners' and occupants' opinions about different building materials, their views on timber dwellings and sustainable materials as well as their willingness to pay a premium for certain materials.
2) Discover perceived issues and benefits surrounding timber in residential development construction that can be explored further in the next stage of data collection that is found in the interview section of this chapter.
3) Determine the difference of opinion between construction practitioners and home occupants with no construction background about increasing the use of timber in new residential and medium-rise apartment projects. The reason for distinguishing between these two groups is to establish whether education and professional experience affects personal perspectives of timber residential construction.

6.2.2 Questionnaire survey methods

A few options were available to administer questionnaires: administered personally, by mail and online. Mail and online questionnaires have benefits to the respondent of being able to complete questions at their own convenience (Sekaran 2000). Some disadvantages of personally administered questionnaires include limited distribution with large time commitments. Mail questionnaires can result in slow response rates and labour intensive analysis of data from written responses (De Vaus 1996).

The Internet seemed an effective way to overcome some of these issues and distributing questionnaires via the Internet reduces the time and cost in producing, distributing, formatting questionnaires and analysing data received in the responses (Hewson et al. 2003). Some disadvantages noted by Sekaran (2000) of this distribution and collection method are the requirement of the participants to be willing, computer literate and have access to a computer. Apart from the willingness factor, computer usage amongst the targeted sample is high in this occupation and so was high in this sample group.

However, it did mean that the sampling technique wasn't random and does not provide a true representation of the entire NSW population. This issue was not of great concern to the researcher due to the comparative nature of the research design and the use of the survey to guide the semi-structured interviews. Random surveys also have the issues of bias that can occur through random web surveys due to 'volunteer effect' factors and 'frequent user' effects (Hewson et al. 2003). Hewson et al. (2003) recommends that user groups and individual contact be used to reduce this bias and maintain more researcher control. This was the strategy undertaken in this research.

6.2.3 Sampling and sampling errors

One of the aims of this study outlined in Section 6.2.1 described the comparison between the opinions and perceptions about structural materials used in residential developments from two different groups. The first group selected were participants with experience in the construction industry and these were chosen for their knowledge not only about the performance of construction materials but for an understanding of the associated environmental issues. This group of participants was recruited via building companies and construction professional institutes using snowballing and referral approaches.

The second group were participants who have no construction industry experience so as to allow a comparison between the two groups. This group of participants was recruited from colleagues, family and friends using snowballing and referral approaches. The criteria for selection were basic computer literacy, elementary understanding of building materials and an interest in sustainability.

Due to these reasons the use of purposive sampling was chosen for distributing questionnaires. In particular judgement sampling was preferred as this method is suitable for the procurement of people with particular knowledge and skills rather than requiring a predetermined portion of people from different groups that is the case with quota sampling (Sekaran 2003). As with other forms of non-random sampling, the generalisability to the population is limited for judgement sampling (Bryman 2008). As discussed earlier the questionnaire data will be serving the purpose of comparing the different opinions between two groups in addition to raising issues for further investigation in the quantitative section of the research.

A range of different construction professionals is represented in the construction group. This was achieved through contacting specific construction professionals and professional affiliation groups. One major issue related to the responses is the anonymity of the survey. This hindered matching the method of distribution to the response rate for each method. The research population and the method of contacting participants have been included in Table 6.1.

Table 6.1 Research sample and contact methods

Sample group	Distribution agency	Contact method	Response issues	Survey reminder
Construction	AIQS	Member email	Current email	Not permitted
	RICS	Online newsletter	Current email Newsletter Volunteer effect	Not permitted
	AIB	Online newsletter		Not permitted
	Peers	Email/snowballing	Identification	Yes
	Construction companies	Email/snowballing		No
Non-construction	Friends	Email/snowballing	Identification	Yes
	Family	Email/snowballing		Yes
	Colleagues	Group email	Volunteer effect	No

Sampling and non-sampling errors was a consideration during choosing the sampling process despite the method chosen being purposive. Sampling error is the difference between the sample and the population from which the sample is derived and non-sampling errors refers to poor sampling framework, poor questioning or non-response issues (Bryman 2004). There are a number of sampling errors that could occur from the purposive sampling in this study. The sampling of construction contacts and the industry groups do not cover the entire construction industry in Australia. The construction contacts were mainly working for the middle to large construction firms, which mean small builders were underrepresented. Three of the larger industry groups agreed to send out the survey however there were a number of industry groups that would not participate. This means that all practitioner groups were not equally accessed and possibly under represented. To minimise sampling errors in the construction practitioner group the participants back was identified in the responses and if required additional recruits would be pursued.

6.2.4 Questionnaire process

The questionnaire was developed using the online survey tool developed by the university in both the pilot study and main study. Questions for the survey were developed based on the literature review. The survey was intended to be conducted online and was made available initially as a test survey to gauge whether questions were appropriate for the population and the aims of the study (Fowler 2002). A pilot was conducted using ten people by invitation from academia, construction profession and those with little or no construction knowledge were family friends.

The pilot study was conducted on 26 September 2011 via an email contact with a survey link for one week. The pilot study was completed on 3 October 2011 and received a 100% response rate from the participants. The questionnaire survey in the pilot consists of five sections. The first section contained demographic questions such as place of residence, age of house occupants and type of housing. The second section asked about the participants' attitudes towards sustainability in general, sustainability in construction and willingness to pay extra for sustainable building materials. The purpose of this section was to gauge participants' general sentiment towards environmental sustainability and its application to the building industry. The third section focused on participants' experiences, perceptions and opinions towards thermal performance of building materials on homes. This line of questioning aimed at revealing perceptions about construction materials and their thermal performance. The fourth section requested views on timber performance characteristics such as fire, cost, time, and maintenance. The fifth and final section focused on the innovative use of timber in high-rise residential apartments with the purpose of discovering the perception of home occupants towards living in tall timber structures and the associated issues and advantages.

The completed pilot survey was analysed and changes incorporated into the original questionnaire survey. The adjustments included reducing the length, cutting out repetitive questions, improving explanatory information whilst making it more concise and providing comment boxes for questions that could be interpreted in a number of different ways. The challenge of the survey was to keep it simple enough to engage those without construction knowledge whilst maintaining questions that would engage construction professionals and draw out some of their technical expertise (Denscombe 2010). The level of technicality was not changed in the questionnaire so it was expected that some surveys would not be completed. To address this issue it was designed with separate parts that would elicit informative responses even if whole questionnaires were not completed. A copy of the final questionnaire survey is included in Appendix 6.1. Table 6.2 shows the final details of the questionnaire used.

6.2 Details of main questionnaire

Section No	No of Questions	Topics investigated	Types of questions
1 Introduction	11	Participation information Background information/ Demographics Home size/occupant No. Home ownership	Multiple choice Numerical entry
2 Sustainable building materials	7	Sustainability Building materials Current home materials Willingness to pay for sustainability	Yes/No Multiple choice Likert scale
3 Cost of heating and cooling	13	Housing thermal performance Cost of heating and cooling Selection of timber envelope sections New home selection	Written responses Multiple choice Yes/No Ranking
4 Timber housing	8	Timber performance e.g. time, cost, fire, aesthetics.	Likert scale Ranking
5 Multi-storey residential timber units	7	Material preference Benefits and concerns of living in a tall timber building Willingness to pay extra for timber unit.	Multiple choice Written response

6.2.5 Distribution

There were a number of issues with the main questionnaires sent out through construction professional groups in that the researcher was given no control over contact details of potential participants and administration personnel managed distribution as these were distributed via construction professional institutes. This affected the timing of distribution and gave limited opportunity for a reminder to be sent through the direct or newsletter email. It was therefore hard to estimate the actual sample size. Hewson et al. (2003) also suggest that a greater response is achieved through direct email rather than postings to news groups. The use of snowballing also makes it difficult to calculate response rates due to the propagation of contacts through the initial willing participant. Reminders could not be sent to all potential participants due to the lack of control over distribution that was initiated through building companies and professional affiliation groups. However, reminders were sent out to known email addresses.

Despite numerous challenges faced in circulating the online questionnaire, the aim of collecting responses with an even mix between construction and non-construction participants was achieved over a period of four months commencing in December 2012 and finishing in March 2013 through a variety of methods, as stated previously. It has been estimated that direct email questionnaires were sent to approximately 1500 people. The remainder were sent through newsletters with the possibility of around 500-1000 recipients. A total of 312 responses were received, amounting to a 10-15% response rate.

6.3 Data analysis

A total of 312 responses were received after reminders were sent. Out of the 312 responses 15 provided inadequate information and were not included in the analysis. The computer program SPSS (Statistical Package for Social Sciences) was used to analyse data received from the questionnaire survey using frequency and cross-tabulation techniques.

6.3.1 Response and analysis of data

i) Demographics

The professions of participants were broken up into major groups of construction practitioners (48%) and those with no construction industry experience (52%). Construction practitioners have been broken into particular professions/specialties as shown in Table 6.3.

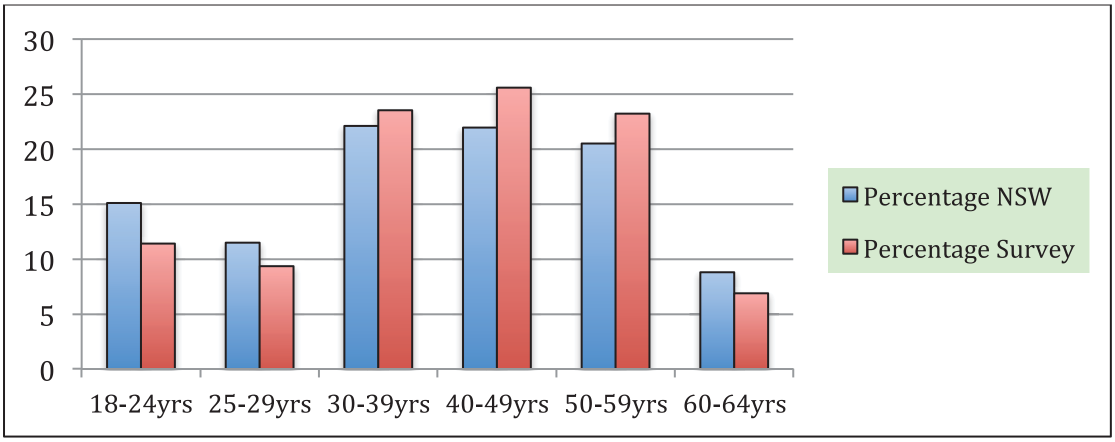
Table 6.3 Questionnaire participant's employment industry background

Construction Practitioner	NO.	PERCENTAGE (%)
Architect	17	5.7
Cost planner	4	1.3
Construction (Builder)	11	3.7
Construction (Project Manager)	33	11.1
Engineer (Construction)	14	4.7
Developer	20	6.7
Property	24	8.1
Building trade	2	0.7
Building related	19	6.4
Total construction practitioners	**144**	**48.4**
Non construction industry	**153**	**51.6**
TOTAL SAMPLE	297	100

Questionnaire respondents' postcodes have been grouped into major regions for ease of discussion although the specific local government areas (LGA) can be found in Appendix 6.2. Inner Sydney supplied the most respondents (48%) followed by outer Sydney (33%), Sydney surrounds (1%), Illawarra (3%), and rural regions (10%), with 5% of respondents failing to provide their postcode.

The basic demographics of the response group revealed a similarity in age to the NSW population (ABS 2012). This is presented in Figure 6.1. Age groups outside 18-64 have been excluded from the demographics as they were poorly represented due to the survey target audience of employed persons, peers and family.

Figure 6.1 Age comparisons between survey participants and NSW population



Source: ABS 2012

Females were underrepresented and made up only 35% of the survey population compared to NSW statistics of 50.2%. This may be due to the construction industry having a low number of female participants (12%). The female survey participants with no construction industry background had a closer representation to the Australian Bureau of Statistics (2012) statistics for NSW women (46% versus 50.2%).

The next section is a discussion of results broken up into sections based on sustainability, timber performance in residential development, cost and time factors relating to timber use in residential construction and material preference for new home purchases. The discussion provides an overview of the issues relevant to the literature review and the research objectives. Only anomalies in the selections related to the demographic groups such as gender, age, and construction experience have been identified in this section.

ii) Sustainability and sustainable materials for residential buildings

The second section of the questionnaire focused on the opinions of participants on sustainability, building materials, timber as a sustainable material and willingness to pay extra for using sustainable products in new homes and renovations. These are shown in Table 6.4.

Table 6.4 Participants views on sustainable building materials and construction

Questions	Participants Response (% of Cross tab group)		
	Agree	Neutral	Disagree
Our society should focus more on preserving our environment	90	7	3
Environmentally sustainable materials should be used to build new homes	94	3	3
Timber is an environmentally sustainable building material	65	29	6
Willing to pay more for sustainable building materials	77	0	23

A majority of the participants agreed that society should focus more on sustainability and that sustainable materials should be used for residential buildings, with percentages of 90% and 94% scored respectively. About two thirds (65%) of participants favoured timber as an environmentally sustainable building material with 29% unsure and 6% rejecting the proposition.

Participants were also asked about their willingness to pay a premium for the use of sustainable building material in a new home build worth $300,000. Approximately 77% would pay more in the new home scenario and the percentage premiums ranged from less than 1% to greater than 10% with the average at 5% or $15,000. As the age of participants increased there was an increasing willingness to pay extra for sustainable materials. Female participants (86%) showed a greater likelihood to pay extra for sustainable materials than males (70%). Construction practitioners were 15% less likely to pay premiums for sustainable materials than non-construction participants.

iii) Thermal performance of building materials

This section discusses the survey responses about each homeowner's perceptions of the thermal performance of their current residence and then focuses specifically on their preference for specific materials used for wall and floor elements in the case of a new home build. The final questions focus on the preference for the use of timber over traditional materials in the building's envelope if it proved greater thermal performance. Table 6.5 provides details of the wall envelope material of participant's homes and their experience of thermal comfort.

Table 6.5 Thermal comfort level of participants

Question	Wall envelope of resident	% of sample	Participants Response (% of Cross tab group)		
			Uncomfortable	Neutral	Comfortable
Year round comfort level of your residence	Brick veneer	33	17	18	65
	Timber	10	38	8	54
	Double brick	48	12	24	64
	Concrete	9	14	41	45

The thermal comfort level of the participants' homes in Table 6.5 was compared to the types of external wall envelope used on them. Out of the total number living in brick veneer, 65% were comfortable, and double brick residents had 64% of residents that were comfortable. Those living with timber and concrete walls had lower year round comfort levels with 54% and 45% respectively. The standout result for dissatisfaction with thermal performance was from those living in timber homes with 38% feeling uncomfortable all year round. The same group was also queried on how many months they found their residence was either too hot or too cold during the year. Timber cladded homes were found to be too hot and too cold for more months of the year than brick veneer, double brick and concrete.

When participants were asked to rank common wall materials for the best thermal performance, double brick received most preferences (55%) followed by aerated concrete (22%), timber (20%) and brick veneer with just 3%. This result was unexpected due to brick veneer being the most commonly used method for external wall construction. However, this may suggest that whilst it is the most popular construction method, participants are not satisfied with its performance and are required to compensate for this through the use of powered heating and cooling.

The top ranking floor material was insulated reinforced concrete receiving 48% preferences followed by reinforced concrete (25%), insulated timber (24%) and traditional non-insulated timber (3%). The anomaly in this result was that insulated concrete and non-insulated concrete options were favoured by construction practitioners (14% and 22% respectively) more than non-construction participants and timber options were elected by a greater percentage (10%) of those not familiar with the construction industry.

When participants were asked if they would build a new home out of insulated timber floors and walls in preference to concrete floor and brick walls if it provided greater insulation, 79% answered yes and of these positive responses 66% would pay an average of an additional 5% on the home's purchase price. Women were more likely to pay higher premiums than males for insulated timber and those in higher age brackets (30-64 years old) would pay higher premiums (10-15% premiums) than the 18-29 year old homeowners. Homeowners with no construction background were also more likely to pay higher premiums (5-15% premiums) than construction practitioners who preferred the 1-2% premiums.

iv) Speed of construction – timber versus traditional materials

Participants' opinions on the speed of construction are found in Table 6.6. Their responses are provided as five options: strongly agree, agree, neutral, disagree or strongly disagree. This discussion has grouped strongly agree and agree together and strongly disagree with disagree in order to reduce confusion.

Table 6.6 Participants' opinions on the speed of timber construction

Question	Cross-tab Group	% of sample	Participants Response (% of Cross tab group)				
			SD	D	N	A	SA
Timber homes are quicker to build than homes with concrete floors/brick external walls	All responses	100	1	5	39	43	12
	Male	64	1	5	33	47	14
	Female	36	0	5	51	35	9
	Construction	49	2	5	27	50	16
	Non-construct	51	0	4	51	36	9
	Living in unit	17	0	6	44	47	3
	Living in home	83	1	4	40	43	12
	Cladding type						
	Brick veneer	31	1	6	37	47	9
	Timber	11	0	4	42	35	19
	Double brick	49	1	5	39	39	16
	Concrete	9	0	9	50	32	9

Table 6.6 summarises the participants' opinions about the speed of timber construction compared to the speed of concrete and brick construction, and reveal that 55% of participants agree that timber homes are quicker when compared to homes built of concrete floors and brick. Approximately 39% of the participants are unsure and only

6% disagree with the claim. The 66% of construction professionals agree that timber is the quickest construction method versus 45% of non-construction professionals. Non-construction professionals are undecided almost twice as often in responses than construction professionals in regard to construction speed (non-construction 51% and construction 27%). Only 7% of construction professionals and 4% of non-construction professionals disagree about the time advantages timber has over concrete and brick.

v) Cost of construction-Timber versus traditional materials

The survey response to the question of cost comparison between timber and brick revealed timber homes are considered cheaper to build than brick homes with concrete floors according to 37% of participants although 45% of respondents are unsure about the cost of building and 18% consider timber more expensive. When looking at gender responses to these questions, 46% of males consider timber homes cheaper than brick compared to 22% of females. More females were unsure about the cost of construction (57%) than males (38%) and just 21% of females and 16% of males believe timber home construction is more expensive than brick homes with concrete floors. A higher percentage of construction practitioners (45%) chose brick homes to be more expensive than timber dwellings compared to non-construction homeowners (31%). The non-construction group was less sure about the cost (52%) than those with construction backgrounds (38%). These figures are shown in Table 6.7 and the discussion used the combined percentages of participant responses (strongly agree and agree) when discussing the positive perspective and (strongly disagree and disagree) to discuss the negative perspective.

Table 6.7 Cost of timber versus heavy materials

Question	Cross-tab Group	% of sample	Participants Response (% of Cross tab group)				
			SD	D	N	A	SA
			Disagree		N	Agree	
Timber homes are more expensive to build than homes with concrete floors/brick external walls.	All responses	100	7	30	45	17	1
	Male	64	10	36	38	15	1
	Female	36	3	19	57	20	1
	Construction	49	11	34	38	17	1
	Non-construct.	51	4	27	52	16	1
	Living in unit	17	0	28	44	28	0
	Living in home	83	8	33	44	15	0
	Cladding type	-					
	Brick veneer	31	5	30	43	20	2
	Timber	11	4	50	42	4	0
	Double brick	49	10	27	44	18	1
	Concrete	9	5	23	59	13	0

vi) Material preference-Timber versus traditional materials

After questions about sustainability, thermal performance, time and cost related to material use for residential buildings were asked, participants were asked to choose between timber and heavy materials if they were to buy a new home or replace their current residence. Results shows that 68% of all participants would prefer to live in a heavy material home when compared with a timber residence. Men were more likely to choose heavy materials (73%) than women (60%) and construction practitioners chose heavy materials (73%) more often than participants with non-construction backgrounds (63%). Age groups also showed differences in percentages of participants preferring heavy materials to timber homes, with 18-39 year olds having a higher inclination for heavy materials than those aged 40-64 years of age.

The participants were also asked the reasons for choosing brick/concrete or timber for a new home build. They were given the option of naming one or more characteristics justifying their selection and these are listed in Table 6.8.

Table 6.8 Reasons for the material choice in residential dwellings

Characteristic	Brick/concrete (%)	Timber (%)
Low maintenance	18	1
Structural performance	16	2
Thermal performance	12	12
Durability	11	0
Aesthetics	10	40
Insect resistance	10	0
Fire resistance	8	0
Cost/Value for money	5	4
Acoustics	4	2
Traditional/Status Quo	4	2
Environmental	1	19
Alterability	1	18
Total	**100**	**100**

The main characteristics for the brick/concrete selection in order of greatest to least were led by low maintenance, structural performance, thermal performance, durability, aesthetics, and insect and fire resistance. Cost, acoustic performance, traditional material, sustainability and ease of altering were selected the least in descending order. Timber characteristics chosen most were aesthetics followed by sustainability, alterability and thermal performance. Cost, acoustics, traditional material, structural performance and low maintenance were chosen with lower frequencies.

6.3.2 Summary of questionnaire survey results

Survey results showed strong support for increasing sustainability generally and in the materials used in residential construction, with most participants declaring a willingness to pay extra for the use of sustainable building materials in residential buildings. Timber was also considered more sustainable than heavy materials. Thermal performance of timber was considered inferior to heavy materials (see Table 6.5) although there was a willingness to use and pay a premium for timber wall and floor envelope system if they outperformed the current heavy material systems. The majority of participants believe that timber construction is quicker than the heavier materials and a greater number thought that timber was cheaper than heavy materials than those who did not. Large numbers of homeowners were unsure about the cost and time impacts of using timber compared to heavy material construction.

When faced with an ultimate choice of purchasing or rebuilding a new home there was a clear majority in favour of the heavy material option. Reasons provided for this choice focused on the perception of heavy materials' capacity to resist issues caused by the natural occurring elements of the environment. These in order of highest to lowest importance are maintenance, structural and thermal performance, durability, insects and fire. Aesthetics and a perception of lower cost were also a reason for the choice of heavy materials. The minority that selected timber for new residential construction had aesthetics, sustainability, alterability and thermal performance as the main reasons for their choice. These material performance issues and barriers to increased timber use raised through the survey will be discussed through interviews with the supply side of the residential development industry along with aspects of cost, time and sustainability.

A number of results that differed between demographic groups are worth mentioning. Females claimed they are more likely to pay more for the use of sustainable materials and greater insulation in the envelopes than males. Males were more confident about their understanding of cost and time performance of building materials than females. Males were more likely to choose heavy materials over timber than females who had a greater affinity for timber. Age factored in the propensity to pay premiums and the choice of timber over heavy materials. The lower age brackets chose lower premiums for the use of sustainable materials and greater insulation and they were more likely to choose heavy materials than the older age groups. The differences in opinions in gender and age groups provide opportunities for further research although this will not be discussed further due to falling outside the scope of this research.

Construction practitioners had less inclination to pay premiums for sustainable materials and would pay lower premiums for greater insulation than participants with no construction experience. A higher percentage of practitioners preferred heavy materials to timber. Construction practitioners were more convinced of the cost and speed advantages of timber compared to non-construction participants. The difference between construction practitioners and non-construction participants demonstrates the impact of construction education and experience within the construction industry to their responses. This will have impacts on the strategies taken to increase the use of more sustainable materials such as timber in residential development.

6.4 Semi-structured interviews

6.4.1 Interview purpose

Survey results indicated that non-construction participants, despite showing a desire to use sustainable building materials, had a number of negative perceptions that did not correlate with the current literature regarding the current performance and capabilities of timber in the residential development market. A number of authors have also outlined opportunities for and constraints of using timber in residential construction in Australia (Bayne & Page 2009; Nolan 2009). The purpose of the semi-structured interviews was to explore issues identified and raised in the questionnaire survey and to ascertain the barriers to and opportunities for timber as seen from the perspective of construction practitioners in the Australian construction sector. Interview questions focus on the use of timber and engineered timber products use in residential projects both in Australia and internationally.

6.4.2 Semi-structured interviews

Interviews can be structured, unstructured or a mix of the two. Structured interviews allow for consistency in the line of questioning to each participant although they fail to capture thoughts or concepts that have not been considered by the interviewer (Bryman 2008). Unstructured interviews can be used when the investigations are entirely exploratory and there are no boundaries to the scope of questioning but this can lead to participants heading down a number of tangents irrelevant to the research topic. Semi-structured interviews were used in this research as this method combines the formal and informal interview methods. The approach ensures the themes mentioned in the survey and the literature were addressed as well as allowing participants to raise perspectives about timber construction. Interviews were carried out face to face rather than over the phone or the Internet to enable the interviewer to build rapport, engage in the thoughts of the participant, and direct the discussion based on the participants' responses and non-verbal expressions (Lofland & Lofland 1995).

6.4.3 Pilot interviews

Three pilot semi-structured interviews were conducted to assist in refining the interview questions and provide interview practice prior to the bulk of the interviews (Forsythe 2003; Silverman 2010). The participants were recruited through business contacts in the construction industry. The literature review and survey results formed the basis of the questions used in these semi-structured interviews and, through the pilot study, a number of other questions were added as a result of the conversations. (Details of these questions were included in Appendix 6.3.). Table 6.9 provides details of the 3 pilot interviewees.

Table 6.9 Pilot interview details

Interviewee Code	Years of experience	Construction specialty	Interview time	Place of interview
1	30-35	Project director, Contract administration	60min	Café near work
2	30-35	Engineer construction/mining	70min	Interviewer's home
3	35+	Architecture	40min	Workplace

The pilot study highlighted a number of issues to be addressed through interview techniques for the main round of interviews. The issues included the participants focusing on unrelated topics and the length of the interviews. To overcome these issues, the time of interview was restricted to 45 minutes both to adhere to the ethics approval (for 45-60 minute interviews) and to minimise the utilisation of a participant's time. Increased control over interviews was the strategy employed to minimise the discussion of topics not relevant to the research. The semi-structured interview questions were finalised and a copy of the questions was included in Appendix 6.3

6.4.4 Sampling and research population

The initial participants were sourced through work colleagues, industry groups and senior construction industry participants. These participants then recommended peers that fit the selection criteria and provided introductions was through emails or phone The purposive sampling method was chosen rather than random sampling in order to obtain the maximum relevant information related to the research (Denzin & Lincoln 2000). Random sampling was not chosen due to the specific experience, knowledge, company background and specialty knowledge required of interviewees. The selection criteria are explained below:

- *Industry Experience* – Interviewees were sourced from a range of years of experience in the construction industry. Included in the sample would be professionals with 5, 10 and over 20 years' experience.
- *Company type* – Participants were chosen from a variety of different size companies in order to represent the opinions of the broad nature of the construction industry in Australia.
- *Construction specialty* – A variety of design and implementation professionals were chosen related to the influence they held over project design and construction methodology.
- *Project experience* – The limited number of professionals in Australia who have experience with timber and engineered timber in residential projects and those currently working on the Australian project or proposed projects were approached for participation.
- *Convenience* – Due to limited time to travel and budgetary constraints the interviews were conducted in Sydney.

Two purposive sampling methods that could have suited this part of the study are theoretical and snowball sampling. Theoretical sampling is the process of collecting data from participants or cases relevant to the research whilst simultaneously coding and analysing which then guides the next stage of data collection (Glaser & Strauss 1967). This method was not chosen due to time restraints and lack of resources to conduct a prolonged exploration into the research issues. Snowballing allows an initial contact with a small group of participants who are relevant to the research to generate other contacts for the researcher that fit the same sampling criteria (Bryman 2008). Snowballing was appropriate and chosen as the sampling technique for the interviews in this study due to the specific criteria required for participants, the homophilic nature of the Australian construction industry, and the option given to survey participants to participate in interviews. The sample was obtained through the initial points of contact that included respondents to the survey questionnaire, invitations to tier one and two construction companies and referrals from academic sources. The secondary contacts made through snowballing were sourced from interviews with the primary contacts. This allowed for the efficient use of time for both the interviewer and participants in addition to the increasing the quantity of relevant data per interview.

The second stage of data collection interviewed 25 professionals currently working in the construction industry. Table 6.10 summarizes their background.

Table 6.10 Main interviewee details

Interviewee	Company Type	Industry Experience
Architect 1	Head contractor	35 + years
Architect 2	Architectural firm	10-15 years
Architect 3	Developer	10-15 years
Architect 4	Architectural firm	5-10 years
Safety officer	Head Contractor	25 + years
Contract Administrator 1	Head contractor	10-15 years
Contract Administrator 2	Head contractor	0-5 years
Structural Engineer 1	Engineering design	30-35 years
Structural Engineer 2	Head Contractor	20 + years
Structural Engineer 3	Consultancy	10 -15 years
Structural Engineer 4	Engineering design	10-15 years
Fire Engineer	Engineering design	5 - 10 years
Project Director	Head contractor	30-35 years
Project Manager/Academic	Client side/University	35 + years
Project Manager 1	Head contractor/Building legislation	10-15 years
Project Manager 2	Head contractor	10 - 15 years
Project Manager 3	Head contractor	5-10 years
Business development manager	Head Contractor/Developer	20 + years
Quantity Surveyor 1	Developer	35 + years
Quantity Surveyor 2	Developer	10-15 years
Quantity Surveyor 3	Consultancy	10-15 years
Quantity Surveyor 4	Consultancy/building legislation	15 - 20 years
Estimator	Head Contractor	5-10 years
Timber industry expert/engineer	Timber development	25 + years
Timber consultant/Academic	Consultant/University	20 + years

Table 6.10 shows the professions of the interview participants, the type of company worked for and time spent in the construction industry. The design practitioners included structural and fire engineers as well as architects. Design professionals could provide some of the technical restraints or benefits of using timber as an alternative to heavy materials. The project team participants included project mangers, cost planners, a safety officer and several contract administrators. Project participants were expected to advise on some of the practical implementation issues related to timber use in large residential construction sites in addition to time and cost, and quality effects of timber use in multi-residential housing. A few interviewees were chosen for their expertise in timber or involvement and understanding of the innovative use of timber in buildings.

There was a potential sampling error with the group due to the topic focuses on sustainable building materials and timber construction. It was more likely that construction participants with an interest in these fields would participate and so representation of those antagonists to sustainable building could be underrepresented. In order to capture some of the challenges and barriers of timber construction questions were presented obtain comment on both the positive and negative aspects of this construction method. This could assist in responses being balanced and based on the experience and practice of participants in addition to their personal perspectives.

6.4.5 Data analysis

Interviewees were asked similar questions at the outset of each interview and then additional topics were explored particular to a participant's profession or when raised by the participants. The initial question was based on the participant's awareness of the world's tallest high-rise engineered timber structure built in Australia. The reason for this question was to ensure that interviewees understood the topic under discussion and to provoke thought about the benefits and challenges of building tall buildings. These were the content of the next couple of questions. After these first few questions, interviewees were asked their opinion on the perceptions of timber that had been raised in research papers, the literature and the questionnaire survey that formed the first part of this data collection. This questioning was used to confirm or dismiss whether perceptions of timber performance were accurate and applicable to the present day Australian construction industry. Further questioning was based on each participant's professional expertise applied to the feasibility of increased timber use (e.g. Cost planners were asked about cost implications through the project cycle of timber use as an alternative to heavy materials). Interviews were recorded and transcribed for use in the analysis stage.

A thematic analysis is typically used in qualitative research and was undertaken through the use of NVivo 9. In this analysis key recurring themes (nodes) were established. The key issues affecting challenges and barriers to and opportunities for increased timber use in residential development in terms of time, cost, performance, sustainability, and perception are listed in Table 6.11. A ranking of importance is attributed to each of the main topics listed based on the number of times issues and benefits related to this topic were mentioned. This is expressed as a percentage (%) and was determined by nodes established in the NVivo 9 report. Each main topic represented a number of factors that will be addressed in more detail in the interview discussion.

Table 6.11 Key issues and benefits of increase timber use in residential construction

Issues and Benefits	Level of importance (%)
Time	25.5
Perception	25
Timber performance (Thermal)	23
Cost	22
Sustainability	4.5
Total	100

i) Time

Time issues and benefits in timber and engineered timber product construction is a very broad topic and interviewees commented on a number of subthemes. These include the efficiency of the construction process, timber's lightweight properties, prefabrication potential, procurement of materials, tendering and trades.

Efficiency was a subtheme mentioned most often in regard to time from a number of perspectives. Issues of dealing with a new system and coordination of trades and suppliers was mentioned by a timber industry expert: "A project manager (PM) is always going to push it back to what they're familiar with, and the supply chains that they're familiar with. It's human nature. Everybody along the design path and the supply path are wanting to use the same old way they've delivered it previously, because it is what they're familiar with." The structures of timber buildings are also installed so quickly that follow on trades may not order materials on time and therefore delays can occur due to misunderstanding the process.

A project manager also commented on the reduction in trucks to site compared to prefabricated concrete or in situ concrete, which in turn reduces vehicle movement supervision and site congestion. The reduction in erection time also reduces time for cranes, time on site for amenities, and for staff both on site and in the company office. This observation was made by a couple of the project managers, contract administrators and cost planners. Both a project manager and contract administrator discussed reduced wastage for prefabricated structural walls and floors as the engineered elements are made-to-order in factories and can be manufactured according to most designs. However, the development manager on a timber project discussed one issue of these products, which is, they are manufactured from rectangle billets and there is waste in creating openings in the panels. Another limitation is their size which is dictated by transport limitations such as shipping containers and truck deliveries and they need to be designed to cater for the modes of transports as well as for construction speed efficiencies.

The construction process for engineered timber residential buildings is usually based on prefabricated panels to varying levels and sizes depending on the size of the project. This is a similar process to pre-cast concrete in residential buildings although some installation advantages for timber were picked up by practitioners. Timber panels are much lighter than concrete panels and this increases the number of panels transported from storage facilities to site, which means fewer truck deliveries and truck movements on site leading to a reduction in time and improved safety on the ground. Another time and cost saving related to its lightweight nature is the size of the crane required to transport panels to each level.

Interviewed timber experts, project managers, contract administrators and cost planners identified the ease with which engineered timber systems are installed, the improvement to the building program, and the avoidance of issues related to formwork in concrete systems. The business development manager on one project viewed the offsite nature of timber fabrication as one of the big advantages and the fact that it can easily modified onsite if minor errors need correcting or modifications are required. He also noted the high dependency on getting the design process right and the necessity of the design and construction participants understanding the design and construct process. A building surveyor also suggested that the lack of experience in larger timber framed buildings could reduce the time efficiencies in the process.

Another issue raised by project managers was weather conditions in relation to wind and rain because if there is a run of high wind days nothing can be completed on the structure due to its crane dependency. The protection of the timber from moisture and the amount of onsite storage required could also cause problems in prolonged periods of rain. Whilst crane delays can be issues on all sites in situ concrete has the advantage that if there materials are delivered to the deck manual fabrication and concrete pour preparation can still occur if the crane is not in operation.

A number of issues were raised regarding prefabricated timber procurement and installation. These include transport, design resolution, terms of contract, and lack of design and trade experience. The issue of lead times with some prefabricated timber products was discussed by practitioners, in particular the 12-16 weeks it would take to receive structural panels from Europe, from the time the manufacturers received the design to arrival in Australia: "like any builder you speak to would prefer to have them locally produced than sitting 12 weeks away in Europe from a number of perspectives. One is if you need it on short notice you can make that happen, you can go and see the product, you can have more ready access to quality control". Whilst long lead times are not unusual in residential construction projects, most materials can be sourced locally if an additional item is required due to damaged imported products or manufacturing errors.

Prefabricated heavy timber panels such as cross laminated timber are only currently manufactured in Europe and this opens up risks in delays due to shipping and road transport and doesn't allow for late design changes. This issue of design also extends to the requirement of having a completed structural design prior to ordering materials and puts considerable pressure on design consultant coordination and design resolution prior to work commencing on site, as described by a senior contract administration: "It would need to be fully documented, all resolved, everything, stuff some shit and you're away, without that, if you were meeting a deadline and you didn't get your order in time you'd be wearing some liquidated damages, so there's still a few risks with it obviously". Whilst this is possible the construction industry is accustomed to design and construction contracts that includes a lot of ongoing design whilst works are in progress. These design and construct contracts with the associated impromptu changes are more suited to in situ concrete construction than prefabricated elements.

Terms of payment can cause problems for medium-sized construction contracting firms if large upfront payments are required by the manufacturer. Developers will not always pay for materials prior to delivery to site so a cash flow issue can occur for the contractor if there are long periods of time between a payment from contractors to manufacturers and payments from the developer to the contractor. The development manager observed that the ordering of the whole timber structure without upfront developer payments would make it impossible for most medium-sized construction firms in Australia to compete in this type of construction methodology. "I think if you are having to pay for the goods when they're being manufactured and then waiting 12 weeks for it to get here on ship that is a cash flow issue for tier two building companies to really deal with".

Another issue identified is the lack of subcontractors available for competitive tendering for the installation of the prefabricated timber structure. This can lead to inflated prices due to monopolisation as only one medium-rise residential timber building has been built in Australia with heavy prefabricated elements. A contract administrator (CA) stated: "there's not enough people out there doing it, I wouldn't be able to tell whether the costs are any good". One solution offered by the CA is to use carpenters on an hourly rate although this adds risk to the contracting builder if installation takes longer than estimated because it not only increases the cost of installation but also impacts on the program and site costs.

In this section on the time benefits and issues of prefabricated timber construction interview participants identified improved time of the construction methodology, simple installation, smaller and reduced crane and trucks movements on site. Simple structure alteration was considered an advantage along with less site work due to the offsite fabrication dependency of panelised timber. Some barriers and issues discussed included the lead and transport time from Europe, a lack of experience in the design and construction process that could lead to premiums in the tendering process, and the high contractual challenge of medium-sized firms to be involved limiting the involvement of construction firms to the few tier building companies in Australia.

ii) Perception

Practitioners spoke of a number of topics related to perception of timber and engineered timber products in residential construction. These include comparison to alternative materials and methods, innovation in the construction industry, education of industry practitioners and tertiary students, as well as marketing and market perception.

Many responses from industry practitioners spoke of timber use in structural elements of larger residential projects based on comparisons to the traditional materials. When discussing their installation, the simple connections in timber structure were compared to the cumbersome and time consuming precast concrete connections and reinforcing requirements required for in situ concrete. This simplicity was seen as a great advantage not just for the structural elements but also for the service installation process as noted by a contract administrator and project manager: “timber is easier to fix to and install, you just screw it in and away you go”. Two cost planners were interested in trying to compare the timber construction costs to concrete structures on a square metre basis: “If you’re just looking at the cost of a suspended slab, if you include formwork and reinforcement then $200 a square metre is close. If I were doing a rough estimate it would be about $240 a square metre, just for the slab itself, a suspended slab. So if they're saying it's three times that type of money, you know, even if its $6-$700 a square metre you would think that it would be pretty hard to claw back those costs through time and other savings".

However, a number of interviewees raised the issue of direct comparison as there were a lot of indirect savings with timber in site related costs such as reduced labour force administration and amenities which make up a significant portion of overheads. One timber project participant confirmed that the actual square metre cost was similar although the main benefits were made up of the cost saving opportunities not considered.

Issues such acoustics in timber were also compared with concrete, despite the perception that concrete performs well acoustically. One timber expert clarified the fact that people don't realise that concrete needs insulation and a floor covering to ensure acoustic compliance with building codes. Fire and thermal performance are also bases for timber comparison to concrete. Although a number of practitioners recognised the capacity of timber to perform well in fires and for thermal adequacy, there were still a number of practitioners interviewed who believed there were high risks by using timber.

The majority of interviewees agreed that educating current and future practitioners was important to support the increase of timber use in residential construction. A few younger practitioners believed that undergraduates should be introduced immediately to timber and engineered timber structures early in their training to allow them to have a basic idea of the system. "I think it's good for students to know what's being tested in the market because it's sort of – from my perspective it's quite exciting to hear of new alternatives, and if you've got an interest in that you'll then track it" and "I think they should teach it, why not. Or even just the awareness of it, that this product could be something that we will be using in the future". Of those who had more experience, two believed that it was worth waiting until the use had increased to a certain number of projects: "It's got to be proven to some extent before you can start teaching it to students, and why hasn't it been done more so far". Others had the belief that once the use had become established and proven to be successful it should be taught both to students and practising designers and project management staff. Some differing opinions surrounded the wait before education should be initiated although 5-10 years was a common time period discussed.

With limited mid-rise timber structures built in Australia, there was conversation with practitioners on the barriers against greater implementation and the response focused on convincing both the practitioners and the general public. One CA suggested that it would take a while for people to adopt the idea and a PM thought that convincing Australia to adopt this way of using timber would be one of the greatest challenges: "The big issue that you're going to get is perception, it's different." Another PM recommended to capture a small section of the market while another CA believed it would take ten years to see just a handful of these buildings completed.

A cost planner who considered himself an early adopter welcomed the new use of engineered timber structures but stated that there would be challenges in convincing the industry because too many people were stuck in traditional roots, particularly when it comes to a building's structure. The business developer also mentioned that it wasn't just a matter of convincing the design consultants and demand side of the market but that a lot of work is required to convince certifying authorities and insurance brokers of the performance of timber in larger buildings than used in previous projects. The other barrier mentioned was convincing "mum and dad investors who don't have any idea of construction or the performance of particular materials and structural systems".

These challenges of overcoming current perceptions of timber performance versus traditional heavy materials are dependent on marketing and the attitude of market participants purchasing the residential properties. One PM considered that the mindsets of people who are used to brick and mortar and reinforced concrete will take a lot of convincing. Another PM believes that the negative perception of industry participants will be overcome once the larger construction firms complete a few buildings in timber and there is a general increase in confidence.

The timber development manager spoke of how they overcame the possibility of the negative demand side perception through educating their sales staff about basic technical issues so they could address concerns raised by potential customers: “in terms of the sales team we did do an education on the system, so to understand the system and the common questions that come up around durability, termites and so on.” They also adjusted their sales strategy by not selling off the plan but allowing people to experience the finished product. This helped convince consumers that the timber system had all the amenities offered in a concrete residential block with the exception that the structure was timber. They also decided on a conventional façade rather than one in timber to provide a similar aesthetic offering to the surrounding heavy material buildings. These strategies and pricing the residence according to the market at the time allowed for any misperceptions about timber use in the residential apartment to be overcome.

The perception of practitioners of timber use in structural applications in large residential buildings reveals that the industry will take some convincing through education of design and project management professionals and undergraduate practitioners, and the completion of a number of successful projects by larger companies to ensure that the system is feasible for other building participants with a lower risk appetite. Successful persuasion of consumers in one project has shown the potential to convince the demand market of the benefits of timber and dissuade them of their negative perspectives. The next section reviews the views about timber performance for the engineered timber structures.

iii) Timber performance

The performance of timber has been discussed in the literature according to past perceptions by practitioners, so this section looks at the perspective of Australian practitioners on the issues they think about with timber structures in large residential buildings. The majority of interview participants mentioned the quality of design, acoustics, durability and fire characteristics. Other issues raised include maintenance and thermal performance.

Attitudes to design quality for timber is important particularly when looking for an alternative for concrete because, although you may be replacing a heavy material with a lighter one, designers are required to consider all the impacts and issues peculiar to timber to ensure efficiencies are maximised. Design needs to consider not only the floor plan layout but also the methods of delivery into the country and onto the site. The number of crane lifts will be determined by the design and the size of prefabricated timber will affect the spans and fixing requirements when in place. A timber expert believes that it would be a lot easier getting architects on side compared to structural engineers and service engineers and ensuring they are willing to be involved early in the project and to work closely with the entire design team. The lack of complete and detailed drawings in time for fabrication can cause time delays to the whole project. The client needs to be thinking of using timber from the beginning to ensure the best result is achieved.

Another design consideration is using a square floor plate rather than curves which is a common efficiency with all materials, Timber, however, is a lot more challenging to produce curves than in situ concrete so this is a limitation of timber at the present. A further design concern is the understanding of designers of the manufacturing process and how their designs can optimise the work completed offsite. This is something implemented with precast concrete although in situ concrete does not require these contemplations in the design stage.

Acoustically solid timber performs quite well in walls and for the high frequency sounds in floors and one engineer appreciates that timber can provide better performance than masonry. However, timber performs inadequately with low frequency sounds and, as discussed by a timber expert, it requires additional mass to avoid the vibrations associated with footfall. This can be achieved through acoustic dampening by tuning the floors or by adding mass in the form of concrete screed that introduces a wet trade before floor coverings are applied. One option suggested to negate the need for onsite-wet trades is to prefabricate timber-concrete composite floors. Acoustics was one of the main performance issues with timber raised by project managers, cost planners, architects and contract administrators and is also one of the main concerns by practitioners found in the literature.

Durability was recognised by survey participants as being a reason for choosing heavy materials over timber in residential construction and it is one of the concerns of practitioners with using timber for a large residential building. The main concerns identified were the infiltration of water from façade and waterproofing failure and internally from leaking water pipes and condensation from air conditioning. Whilst one engineer had contradicting views and understood the benefits of timber's hydroscopic characteristics, he was also concerned about moisture that was continuous or had no way of escaping.

Bathroom waterproofing was a big concern for practitioners as damage from failed waterproofing is significant in Australia's concrete apartment buildings. The tall timber building in Australia utilised prefabricated bathroom modules to avoid any moisture issues. Despite these concerns, minor damage can be fixed quite easily by cutting and plugging although there may be challenges repairing major structural effects caused by moisture. Termites was also flagged as a potential barrier and the timber expert contributed it to the fear factor and suggested that the lower floor would be the primary concern. The timber development manager discussed the both termites and water issues in the context of detailing and thought that there are always design solutions and that the main problem was in the correct details and workmanship. The majority of insect and moisture issues in residential buildings are not the problem of a lack of technologies or products but through poor installation or design quality, yet the fear factor is a significant factor for Australians.

Fire is one of the major concerns raised by practitioners in terms of the construction stage, passive fire protection and remediation of fire damage. A safety officer with experience in working on large construction sites did not see a greater risk of fires arising when compared to concrete structures if appropriate measures were implemented and made reference to recent fires on concrete structure work sites. He also admitted that timber could be an issue once a fire got hold due to the amount of fuel available and limited fire fighting equipment. The memory of the big fires in the old wool sheds concerned an older project director in terms of fire control and protection of the structure.

An architect mentioned compliance with the building codes and one PM had concerns about having to demolish the whole building if one floor or part of it was destroyed. The business development manager in the timber project confirmed concerns regarding building code compliance, as managers had to go through a complex process of fire engineering solutions, and negotiation with the fire authorities, insurance companies and building certifiers. This has given the developer information for future projects but this intellectual property will only serve to give the company a competitive advantage: "once you've done a couple of these and they've got all that information in a Bible and they don't have to redo that couple of hundred grand that it cost them, ten grand a test whatever he was saying, you don't have to do that anymore and then straight away you're saving, bang, you don't have to spend that money this time round, you're looking much better." Changes to the building codes are required to simplify the use of timber in larger buildings in Australia. The fire solution undertaken in Australia's first tall engineered timber building was the use of fire resistance plasterboard and a sprinkler system to ensure occupant egress safety. A fire engineer predicted that fire engineered solutions to tall timber residential buildings shouldn't create to great a problem in the future due to more and more large buildings requiring input from fire engineers leading to a growing body of knowledge in the field and increased efficiencies.

Maintenance was considered a significant issue with timber and engineered timber systems implemented without a long history of use in taller buildings to illuminate particular issues. A CA mentioned the limited obligations on developers of buildings once the defect time frames have expired down the track. This is an issue with a lot of residential buildings regardless of the material type and it remains the problem of the body corporate and individual owners to rectify and bear the associated remedial costs. Specific issues include possible cracking with shrinkage and changing humidity, and mould behind wall and floor linings. The pilot building in Australia has moisture monitors installed so it will be part of ongoing observation to how these structures perform over a long period of time.

Structural performance of timber and engineered timber was queried during the interviews with one PM suggesting that "the structural elements has got to be one of the limiting factors" and another design manger commenting that "people would generally prefer the solidity of materials such as brick and concrete". Engineers were confident with the structural adequacy in both earthquake and wind, although there was a question on the limitation on the potential height of a structure using platform construction due to the compression across the grain for timber. This was one barrier to height with this type of timber construction but other methods can overcome this issue although they could impact on the speed of structural erection and reduce the associated benefits. Some proposed taller timber buildings incorporate the use of other materials such as steel and concrete to overcome structural limitations of the timber only options. Thermal performance was mentioned negatively by one CA in the context of lacking thermal mass potential. All other practitioners were in favour of using timber for its thermal capabilities.

iv) Cost

The financial challenge of timber residential building construction in Australia can include the financing and interest costs, cost of materials, environmental requirements and work, health and safety (WH&S costs in addition to the intensive use of consultants required for certification (Nolan 2009).

Safety cost benefits associated with using mass timber panels include the reduction in supervising/training/inductions related to a smaller site work force and other particular aspects of site safety. A site safety officer believes that "you would save thousands in not having to check and certify special edge protection". There is also a reduction in onsite personnel, noted by a PM commenting, "instead of having 50-60 people running around you might have half a dozen. You have less problems, less safety issues, less scaffolding and you don't need safety screens."

The CA perspective revealed that an unfamiliar timber structure having a lack of specialised installers could present a challenge in finding competitive pricing and having the risk of being unable to procure a fair fixed price due to subcontractors adding risk margins to prices. This also creates difficulties for contractors attempting to put in competitive bids for work. "When builders are pricing they can also put risk margins of up to 25% for unknown risks when pricing the structure and this causes an issue in preliminary pricing and when obtaining financing from banks because you don't want to be telling them its going to cost much more than a typical reinforced concrete or steel structure or the banks would scared off and you wouldn't get your money." Other CA issues raised are the cost of shipping/freight and bank guarantees, and the burden of subcontractors carrying material costs prior to installation. One CA summed up his position from a head contractor's perspective. "Look, until it becomes cost effective I don't think it will be used a huge amount".

Pricing is also an issue at the feasibility stage with cost planners thinking purely in square metre installed rates so as to be able to compare with reinforced or post tensioned concrete. "Cost consultants generally go off their own cost databases of standard prices but the problem is they don't have proper prices for engineered timber e.g. CLT buildings so they tend to price up a lot to cover themselves so the client thinks it is too expensive". This doesn't however take into account the savings from reduced preliminaries cost such as site set up, a smaller work force and a reduction in man and material transport. There are other unseen cost savings in reduced footing sizes, excavation, waste and administration costs. These are all the immeasurable costs from a material and labour allowance perspective although one PM believed that if you can get the thing up 20% faster there could be huge benefit because "with any reasonable size job say 40 million you might have preliminaries of 10 thousand dollars a day. Time on site is everything; it outweighs the cost of material significantly. If you can build something in 8 months instead of 9 months from a building point of view you are saving a lot of money".

Clients/developers ultimately make the final choice for the types of projects they fund and build so they need to be viable financially unless some other motivation is driving them. Practitioners agreed that clients need to choose to build out of timber elements and have to want to pay for it. As a PM commented: "it doesn't matter what the architect may think if the client doesn't think he will get a return it will not happen. Most clients at the end of the day are only interested in cost. They don't care about anything else. It sounds awful but they don't. They want to get maximum return on their investment and that's it. If the developer doesn't think he can get a return on timber its not going to happen".

Consultants all have different roles in projects and different motivations to use innovative construction methodologies. The timber industry expert suggested that cost planners are "a pain to work with" because they don't really price projects; they just use their previous experience. This is a challenge, with only one engineered timber apartment project in Australia, until a few more buildings are complete and the actual cost savings are documented and used for reference in future projects. Another issue with engineered timber systems such as CLT structure methodology is that it is mainly built in a factory so it is important to get designers understanding what the factory can and can't do and how many crane lifts are required and how site assembly works. This is similar to the issues with precast concrete construction. Prefab construction is not as common as in situ building so most designers are more conscious of site constructability issues over offsite fabrication.

In terms of timber design there is a perception that consultants' fees would be significantly cheaper because they don't have to design all the reinforcing and all the shear walls. However, a lot more upfront design resolution is required to achieve an acceptable prefabricated product. In deciding initial building design, it's the architect and developer working together to determine what type of building will meet the developer's objectives. One architect said that "as architects we usually start with the materials and then the materials will be changed through value management". This is usually the result of the cost planner's input although it is important that 'cost consultants who are brought in early to advise a client who needs to know some accurate costs so that timber isn't ruled out early in the process unfairly when it may in fact be a competitive option. A PM commented: "I was working on a project where we were extending a building by three floors and the Architect wanted to use timber. It didn't take long to get rid of that idea. It was going to cost a fortune." These sometimes opposing roles cause conflict and appropriate investment is required to ensure consultant cooperation at the early stages of design. Design consultants admitted "consultant coordination is poor when the fees are low as everyone does their own part and isn't interested in coordinating. Usually architects are better at service coordination than project managers. The project mangers are more financially driven. They don't want anything to interfere with the schedule or budget so innovation is far from their agenda, as it will cost more money. Their reputation is also at risk. If the budget blows out they may not get future work with the client."

The size of the building the client requires also impacts on the financial viability of the materials used; timber, reinforced concrete and steel having different financial efficiencies depending upon the height and floor spans of the specific building. The timber expert recommended "timber frame and unreinforced masonry is suitable for up to 3-4 storeys and can be used up to 7-8 storeys but with diminishing return. Whereas you look at steel and concrete and it doesn't really become economical until you have a repeat on your formwork of at least 5 storeys. Timber frame is half the cost of engineered timber in your 3 storeys so it would be a waste to use engineered timber in this situation. However there is a zone between 5-10 storeys where alternative systems such as engineered timber are competitive." The timber expert believes it will be the tier one contractors who work out the ideal height for prefabricated timber panels as considerations such as extra fire engineering are required after certain heights

The financial viability from a comparison between other material alternatives is that CLT will be a cost comparative option even without some of the time and trade savings. The business development manager claimed: "Our view is that we can get CLT to be cost comparable to conventional construction and have 30% speed advantage and trade savings on top. It should also present more benefits as the industry adopts the system down the track. For example, the greater degree of pre-planning and design resolution reduces the time on site and decreases both economic a safety risks. We are at the real beginning of the system so in ten jobs from now if we really try and capture the efficiencies and cost savings along the way I think this is a better approach. You don't just do one job and solve all the problems. If you have belief in the system that it's going to work you invest in it to make it work."

v) Sustainability

Two of the drivers for the use of timber in structural elements of residential buildings is both the perceived environmentally sustainable benefits of reduced embodied energy and the sequestration of carbon within the timber. Timber buildings' environmental benefits are positive attributes and attractive to the high-end residential market. An architect stated that “I think it has stored carbon which is probably going to be inviting for some consumers. Usually those that can afford to be environmentally conscious” and “If people realise that it’s carbon neutral and has all the other environmental benefits you would certainly have people interested. If it was price neutral it would not be just the super wealthy but the average person might be quite interested and if it was cheaper then it would certainly very competitive.” A cost planner agreed that people are becoming more aware of ESD principles but may not have the confidence that the risk of timber in buildings will pay off. They suggest that people would be more willing to be involved if it was a similar price to traditional heavy materials. However, from a developer’s perspective, “if you can’t achieve 5 star green star rating and get some sale advantage then you are just investing more and more dollars without any advantage”. Additional comments from interviewed construction practitioners from both positive and sceptical perspectives are summarised in Table 6.11. The different construction practitioners have been listed abbreviated in the right column. The key to these abbreviations is provided below.

Table 6.11 Summary of practitioner’s perception of sustainability of timber

	Construction professional’s comments	Profession
Sceptical view	If it proves to be good environmentally then it is great	CA
	You have all the transportation and tree growing issues	CA
	I haven’t seen definitive proof to say timber is better than steel or concrete	CA
	I am not sure anyone has really looked into it and said what is best	CA
	The jury is still out.	CA
	When building companies are doing dodgy stuff with the environmental background of materials how can you really tell?	CA
	I think a lot more research needs to be done in terms of environmental issues-with all materials, not just timber	CA
	I don’t think a politician is going to change things just because he wants a more sustainable building	PM
	When sustainability requirements mean that its beneficial to use timber	E
	You then have to convince the community to live in a sustainable building	E
	People didn’t want to spend the extra money to get the environ. benefits	A
	I don’t think it will be driven by the green market	A
	Usually those that can afford to environmentally conscious	TE
	If carbon becomes equitable to a value proposition	TE
	It will depend on how much sustainable buildings are mandated and the are for environmentally sustainable buildings	TE
	My first thoughts wouldn’t be carbon entrapment but it would come down to dollars	CP
Positive view	Architects are also environmentally aware so the carbon capture is not lost on them	TE
	A contribution towards ecological living	E
	This would have green star benefits which is even considered important for buyers now	A

	Construction professional's comments	Profession
	The fact that it could be carbon neutral is a big tick for it	A
	With carbon reduction becoming a big thing with embodied energy and its really hard to reduce the energy in concrete buildings	A
	Its obviously a sustainable building but did someone do an LCA	CP
	Using sustainable products is also a benefit	PM
	It definitely has a place in sustainability	PM
	Look an innovative product with environmental benefits may have an advantage over conventional methods	CA
	If the government was serious about sustainability they would incentivise developers to make their buildings more sustainable	TE
	If you give some benefits in going greener that may work	TE
	Its just a matter of incentivising developers by allowing an extra storey for reduced carbon	TE
	Everything is so well insulated now that we need to look at embodied energy	TE
	It really has to hit the sustainable market which is growing	CP
	With the carbon and ESD issues it is going berzerk	CP
	We put on a percentage for ESD provisions. Anything over 100 million we put on 2% and if it's under 100 million we put on 4%.	CP
	People are becoming more aware of ESD issues	CP
	I think sustainability is a fundamental thing we do……….so it's an important issue for us	BM
	The macro issues that needed to be addressed such as safety, sustainability, urban generation and having more of a social conscience	BM
	Its ease of working with can easily be altered on site, lightweight and sustainable.	BM
	It's about an environmentally friendly work material that everyone can benefit from	BM

Note:
CA - Contract administrator
A - Architect
TE - Timber expert
PM - Project manager
E - Engineer
CP - Cost planner

A wide variety of different views are listed in Table 6.11 about sustainability in structural timber use in residential construction so an overview has been included below:

- There is some doubt in the current claims of sustainability on timber building products in general
- Sustainability in construction needs to be regulated/enforced
- Financial incentives are required for a greater uptake in sustainable construction
- There is a growing awareness of sustainability in the industry and also in the market

6.4.6 Summary of semi-structured interviews

The interviews raised some significant issues and benefits with using timber in residential development. Most construction practitioners took a personal perspective based on the impact timber would make on the success of a particular project. This is reflected in the dominance of practitioner initial concerns with the cost of timber buildings and the potential delays with legislative processes. The lack of specialists in using timber raised fears of trade and consultant monopolies driving up costs and removing competitive tendering processes. Time was also critical for practitioners in the area of supply and installation. Lack of suppliers was considered a significant time risk whilst speed of construction was seen as a big advantage to the process bringing cost and safety benefits projects of all sizes. Fear of fire or structural inadequacy was not forefront in the minds of the practitioners however the upfront design process and contractual arrangements with suppliers and subcontractors was seen as significant concerns. Sustainability raised a lot of comment during interviews ranging from the slightly sceptical to enthusiastic yet most support for timber uptake in residential development based on sustainability was tied to performance criteria such as cost, time and quality.

6.5 Conclusion

This chapter analysed the results from a questionnaire survey and semi-structured interviews in NSW. The survey had similar numbers of participants from construction practitioners and those from non-construction backgrounds. Results revealed that the majority of participants believed timber is a sustainable material and its use in residential construction should be encouraged. In addition, the majority of participants would pay a premium for a new home build with timber as an important sustainable material replacing traditional heavy materials. Other benefits of timber were found to be that it offers opportunities to speed up the construction process and achieve cost efficiencies, and is aesthetically pleasing.

Barriers and issues associated with timber use in residential buildings are poor thermal performance, high maintenance, uncertain structural capacity, low durability, and susceptibility to insect attack and fire damage. These perceptions are not all accurate according to the literature and research studies. There was a differing perspective between practitioners and non-construction participants. Construction practitioners were concerned with the project related issues such as time, cost, transport logistics and lack of existing experienced contractors rather than technical problems such as ensuring the durability and structural integrity of timber structures. The probable reason for this perspective is that construction professionals have an awareness of the technical and design solutions for timber durability yet are more concerned with the impacts of finding these solutions to the success of the project.

Challenges, barriers and benefits raised in the survey were explored further in the interviews and revealed some similar themes in additional to new topics particular to the supply side of the construction industry. The semi-structured interviews included construction practitioners from a number of specialties including architecture and engineering, project managers, cost planners, building surveyors and contract administrators. A couple of participants had been involved or closely linked to the first high-rise engineered timber residential project in Melbourne, Australia. These included a timber expert and a business development manager for the project. Interviews revealed a mixture of conflicting responses regarding the main themes of time, timber performance, perception, cost and sustainability.

There were perceived advantages of quicker construction yet concerns of product procurement, legislative barriers, contractual issues and lack of experience in the industry about the construction process. Most practitioners believed that both the public and practitioners needed to be convinced of the benefits of timber but disagreed over the time frame for educating practitioners. There were concerns about timber performance in fire and acoustics yet no problems with thermal capability. The cost of timber construction was almost unanimously believed to be the key factor over the other major barriers because practitioners could not see timber projects commencing without an attached financial benefit. Perspectives about sustainability were both positive and sceptical and rated lower in importance to all other themes discussed. The next chapter will identify the current residential development model using heavy materials and develop a sustainable residential development model using timber as the alternative material.

Chapter 7 Towards a sustainable residential development model

7.1 Introduction

This chapter will discuss construction innovation and the challenge of introducing change in the construction industry. It will also look at the stages in the building procurement process in Australia that present opportunities for increased timber use in residential buildings. Data results from the survey and interviews will be reviewed to identify challenges currently hindering the implementation of timber in residential development in Australia. The composition of a proposed sustainable development model for residential construction will be presented in addition to the identification of the key performance attributes that can be used to test it.

7.2 Innovation in the construction industry

As discussed in Chapter 3, timber is starting to be used in large multi-storey residential projects but, if it follows typical industry innovations, it can take two to three decades to become part of regular practices within the sector (Stoneman 2002). Product innovation implementation in a broad range of industries often experience high rates of project cancellation and failure, and success is quite unpredictable (Christensen, Cizik & Cizik 2008). This can deter many companies from adopting significant change, while understanding client motivations and customer expectations can reduce the risks of innovation implementation (Christensen, Cizik & Cizik 2008). Diffusion of technologies, innovation and efficiencies often commence with one firm and are gradually adopted at an increasing rate until competition in the market is significant enough to deter additional players (Kettner, Koppl & Schleicher. 2008). The construction industry is no different and is considered an industry that is slow to change in the presence of technological advances (Widen 2006). The characteristics that contribute to the construction industry's sluggish response to change have been documented by a number of authors including Slaughter (1998) and Widen (2006). These include the following attributes:

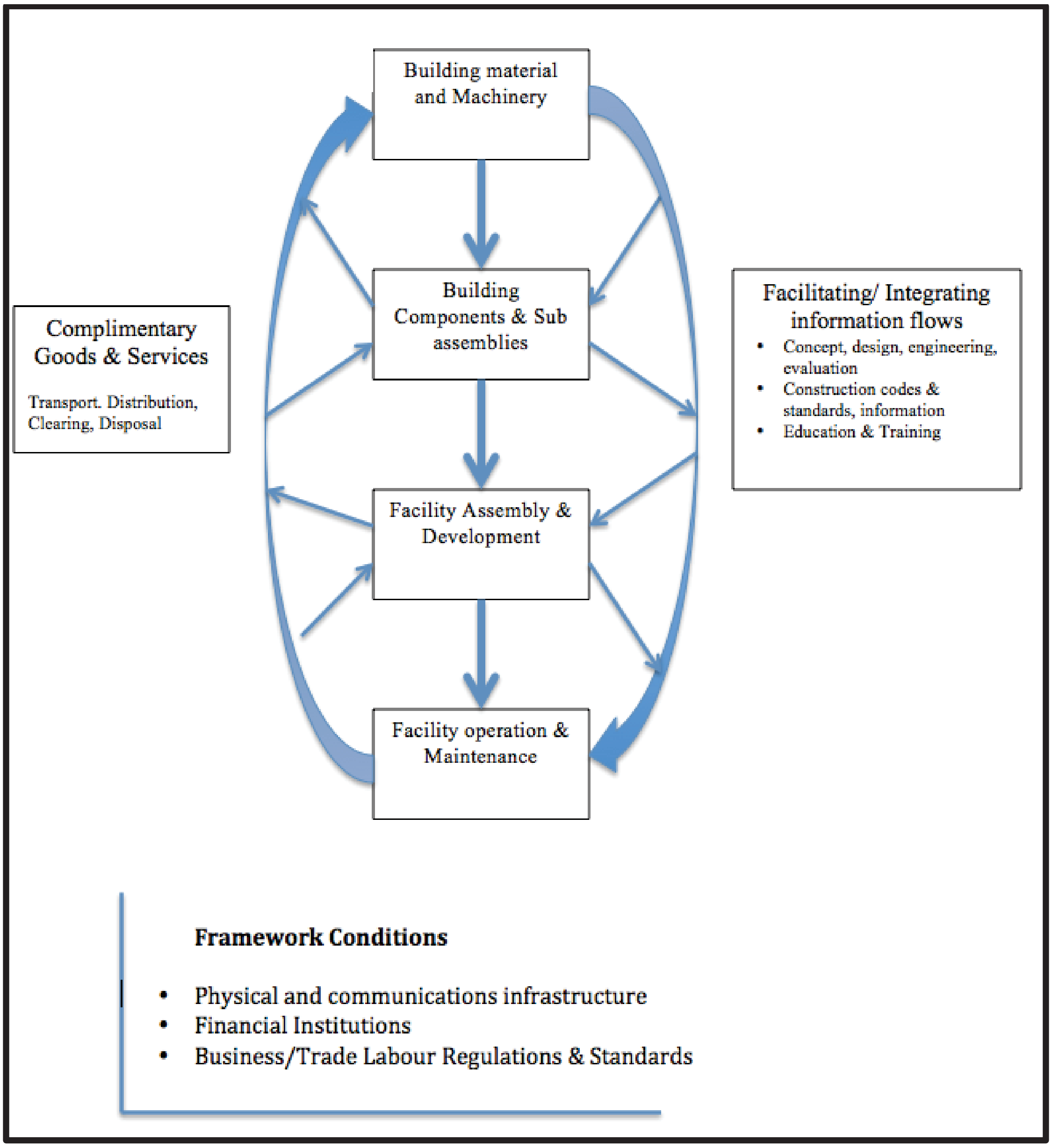
- Unique projects that must meet particular functional purposes
- Client driven needs often limited by time and financial resources
- Distinct sites that require particular solutions
- Continual varying teams involved in design, manufacturing and fabrication of the building, reducing the sharing of lessons learned

Richstein et al. (2005) attribute such characteristics for slowing the transfer of knowledge from one project to another. They also hinder the propagation of information and valuable lessons learned from particular projects to other projects or the wider industry as the information often remains with individuals and within the archives of participating companies (Richstein et al. 2005).

Included in the challenges to construction innovation and efficiency in developed nations is the access to cheap local labour and materials (Seaden & Manseau 2001). Although cheap labour is no longer readily available for construction in Australia there has been a recent increase of construction imports in the form of materials and fabricated elements from developing countries. This has assisted larger companies to achieve cost reductions and efficiencies in the supply of expensive materials and envelope systems. Porter (1998) suggested that innovation strategies for Western companies needed to focus on process efficiencies and integration of competencies in addition to improvements in technology based solutions. One technology that has been advanced rapidly in the design stages of construction projects is the use of building information modelling (BIM). This is becoming a growing solution through construction project life cycles to manage the sharing and exchange of information although industry wide adoption is proving a slow process (Beceri-Gerber et al. 2012; Motawa & Almarshad 2013). Other phases of the project life cycle have not seen as many significant changes so whilst larger players in the industry have implemented technologies and innovative supply strategies the complexity of the building industry is presenting barriers to efficient innovation adoption in all but the biggest players. This is discussed in the next section.

Seaden and Manseau (2001) in their international study of construction innovation developed a framework for analysing innovation systems in construction. They identified some key actors in the industry that have the opportunity to undertake innovation. The framework and relationships between these actors are represented in Figure 7.1.

Figure 7.1 Key agents, interactions and framework conditions in the construction sector



Source: Adapted from Seaden & Manseau 2001

The framework in Figure 7.1 presents an interdependent system with a high level of interaction between the players in the building life cycle. These complex interactions create challenges when attempting to implement a change such as using a new material or structural system due to the number of players and processes affected. A change in the material used for building will affect, and be affected by the interactions and capabilities of the following actors of the system as identified by Seaden and Manseau (2001):

- Building material supplier
- Machinery manufacturers
- Building component manufacturers
- Sub-assemblers (trades)
- Builders and developers
- Facility managers
- Providers of knowledge/information (consultants, training institutions, professional associations)
- Providers of complimentary goods and services (transport, cleaning, demolition, disposal)
- Institutional actors providing the business framework (physical and communication infrastructure, financial institutions, business/trade/ labour regulations)

An increase in timber use in structural systems as an alternative material to heavy materials would affect a number of key players and relationships. The main supplier would be different, as would the machines used to produce the timber components along with their transport and material handling. Trades people for a timber structure would typically be carpenters rather than the usual form workers, steel fixers and concreters required with reinforced concrete buildings. Designers and service engineers/trades would need to understand the new system so training providers and construction education institutions would need to change their curricula. Finally, financiers, insurance companies, approval processes and maintenance managers would also be affected.

This example demonstrates the intricacy and variety of relationships in the building cycle and present reasons for the reluctance and tardiness of players in the construction industry towards innovation and change in building processes. The next section presents a summary of barriers to adapting sustainable materials into Australia's residential building sector. It also presents a recap of the traditional materials used in construction and some recent innovations in structural systems. It then discusses Australia's building procurement pathway and the stages at which increased timber usage could be implemented. It also draws on the perspectives of interview and survey participants to examine the issues surrounding timber implementation.

7.3 Barriers and challenges of adapting sustainable materials to residential construction

A number of barriers were identified during the literature review and data analysis phase of this thesis to using sustainable building materials in the Australian residential building sector. These include the dependence on embedded processes using heavy materials such as reinforced concrete and masonry products. Replacing heavy materials with sustainable materials will require a change in the procurement process of residential buildings and a change in the perception of clients, developers, construction practitioners and end users towards sustainable materials such as timber.

7.3.1 Current material use and practice in residential development

The high use of concrete, steel and heavy materials other than timber for framing and structural building elements are widespread across a number of nations for the construction of multi-level buildings (SCB 2007; TWC 2006; Mahapatra & Gustavvson 2009; Bayne & Page 2009). In Australia the same is true, with concrete and steel dominating the multi-residential market (Nolan 2009). Reinforced concrete has over 90% market share in Australia and column, beam and in situ slabs are commonly used for multi-residential buildings (TWC 2006). Innovations over the last few decades in this sector in terms of construction methodology for structure and materials include the use of precast concrete wall and floor elements, table forms for slabs and prefabricated column form as well as post tensioned reinforcement. More recently, permanent formwork systems for walls with attached linings have been utilised to increase floor level completion times and reduce costs and delays to follow on trades through minimising formwork clutter internally. The focus for structural system efficiencies in multi-storey buildings is based on the reinforced concrete system, which is perceived to be the optimum material for this purpose and with which the construction industry has become accustomed. A shift to using a sustainable material such as timber will require change to design thinking, workforce structure, supply chains, planning and construction methodology.

An increase in timber use will not only require changes in the processes and relationships in the Australian construction industry but will also require the addressing of current barriers to innovation in construction. An early study by Slaughter (1998) investigating models of construction innovation claimed that minor innovation in construction was common when it had only minor impacts on a few industry actors. The study also identified that major construction innovations (e.g. new structural material or a new process) were faced with many challenges that included fabrication issues, component and system integration (Slaughter 1998). Other barriers to innovation in construction identified by Seaden and Manseau (2001) include the lack of investment in research and development, restrictive government policies, lack of industry participant collaboration, large numbers of interactions and slow response to technological change.

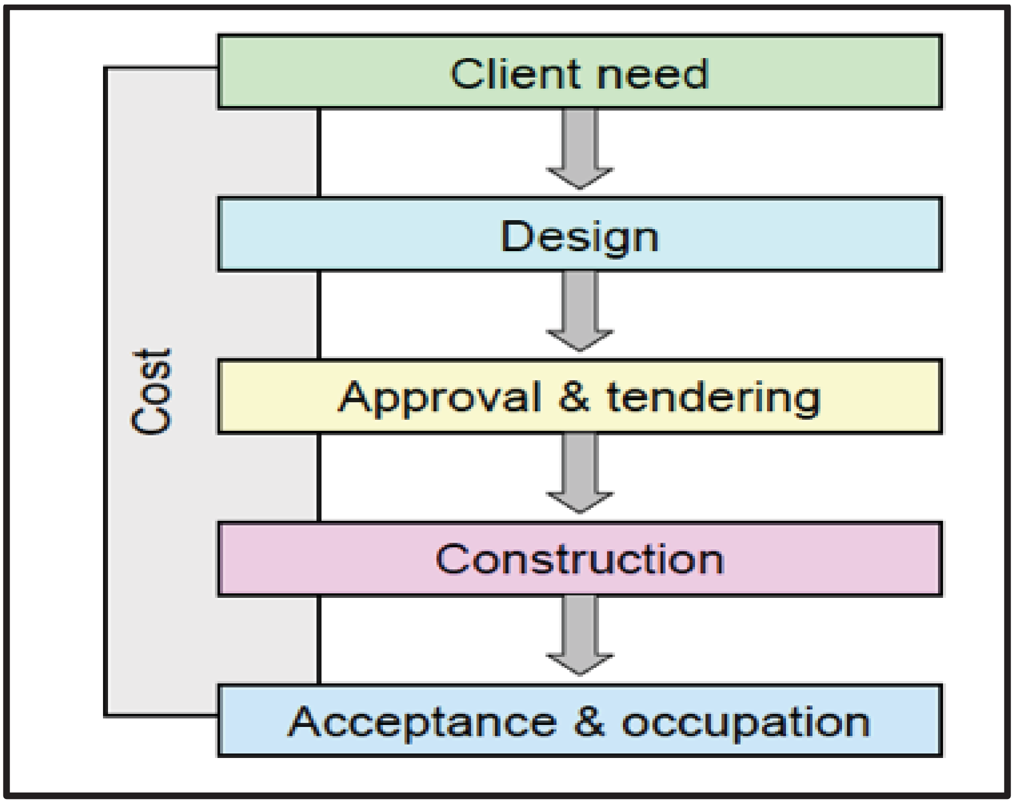
Blayse and Manley (2004) confirmed that isolated projects, complex interactions and government policy acted as barriers to construction innovation. Other barriers include the time consuming and expensive process required for testing new products and the necessity for an available supply of replacement components/materials. Their study also identified as challenges to innovation traditional management approaches, multiple overlapping individual work packages and a majority of small players in the industry (Blayse & Mansley

2004). In order to facilitate change and innovation in the construction industry it is critical to gain support from the key stakeholders, in particular the client. The client is considered the key promoter of construction innovation and this has been the view held by a number of previous researchers (Winch 1998; Barlow 2000). The next section looks at the critical stages in the Australian construction procurement process during which sustainable material use has the greatest chance of implementation success.

7.3.2 The construction procurement process in Australia

In Nolan's 2009 study of opportunities for and constraints on timber use in the Australian construction industry, he identified the steps that influenced the use of timber during the building procurement process. Figure 7.2 shows these steps diagrammatically.

Figure 7.2 The building procurement process



Source: Nolan 2009

The main building procurement processes as shown in Figure 7.2 are client need, design, approval and tendering, construction, acceptance and occupation. These have been expanded along with the particular actors that are involved in each of the procurement stages in Table 7.1. The third column in Table 7.1 identifies the barriers to timber based on the literature and the results from interviews and questionnaires that formed the data collection for this study.

Table 7.1 Barriers to timber use in the residential building procurement cycle

Procurement stage	Actors involved	Barriers to timber
Client need/ Feasibility	Client Project manager Cost planner Financial	Unpredictable profits Demand side perception
Design	Cost planner Architects Structural engineers Service engineers Project manager	Lack of experience Resolved design req. Consultant cooperation Unknown costs Perception of timber performance
Approval	Building codes Aust. Standards Government/Council Fire authority Certifiers Sustainability regulations	Building code (non-compliant) Fire testing and reports (cost/time) Fire authorities approval process Knowledge gaps for certifiers Sustainable benefits not recognised
Tendering/contracts	Project management Head contractor Transport Trades Material suppliers Equipment provider	Lack of experience of trade Less competitive tenders Importing costs and time risks Cash flow issues Dependency on cranes Lack of cost information
Construction	Project management Head contractor	Trade coordination Program control
Acceptance/maintenance	Client Project manager	Warranties/ performance Maintenance schedules
Disposal and recycling	Demolition co. Waste/recycling centres Legislation	Cost of separation and reuse Future legislation requirements

Sources: Seaden & Manseau 2001; Nolan 2009; Data analysis results

Table 7.1 contains a summary of the barriers identified in the literature and data results and allocates them to the particular procurement stage of the construction process. It also identifies the actors involved in the various stages of construction. The following section discusses the barriers identified in the data results according to the procurement stage of construction. The first part of each stage is based on the literature and the second part on the data.

i) Client need

Client need relates to the function and purpose of the building and the price the client is willing to pay for it. The client differs with the size of the building, with homeowners usually procuring individual residences and developers commissioning the construction of multi-storey apartments (Nolan 2009). Developers and clients building for a profit are more likely to be dissenters against a construction innovation and conservative in their choices of materials in order to limit capital cost (Ivory 2005). Home purchasers are subject to the designs on offer by volume homebuilders and their own budgets unless they are the minority who choose to work with an architect to design and build a bespoke home (Forsythe, Davidson & Phua 2010).

Interview data results confirmed that most developers are profit motivated and that the risks associated with the current timber multi-storey construction methodology need to be reduced in a number of areas. These include the availability of reliable cost data so that feasibilities can be carried out at project initiation and the sustainability benefits of using timber for marketing purposes. Public perception was identified as important for many developers if they are planning to sell their apartments. Developers of volume housing also need both positive demand perception and reliable cost information to encourage investment in a new design that requires a change in their marketing, material supply chains and trade procurement and scheduling. The client in detached housing is often the intended occupier or landlord of the home and the survey data showed they have some different concerns to the clients of multi-storey developments. In addition to having a home built for a competitive price and appropriate design/floor plan, they also have an interest in low maintenance, good thermal performance and capacity to resist rot and insect attack. An increase in timber use driven by the client will require accurate cost data and a positive perception of the cost and performance of timber.

ii) Design

Volume builders usually procure architects and draftspersons to produce designs for detached housing with the occasional input of structural engineers to produce a limited set of designs (Nolan 2009). Multi-storey construction utilises multidisciplinary design and cost teams lead by project managers to complete the designs. This is an ongoing, complex process driven primarily by cost and end use function and involves geotechnical/structural/fire/hydraulic and mechanical engineers along with cost planners, architects and design managers. Designers working in multi-disciplinary teams already experience the challenge of limited knowledge sharing, so introducing a technology of innovation is likely to add complexity to the process (Carrillo, Anumba & Kamara 2000). Deviation from typical material use in these larger projects is uncommon and adopted only to achieve particular criteria driven by the client's needs or desires. The alternative material must not just fulfil client needs but also be fit for purpose, be economic and easily available for supply, and not present installation challenges. New or different materials can place additional burdens on designers, fabricators, regulatory approval processes and installers and therefore is often met with resistance from project participants.

Design is a critical part of timber's inclusion in multi-storey residential projects as discussed in the interviews with construction practitioners. Results showed that the design phases for timber developments compared to traditional materials is a lot more extensive, requires a higher degree of resolution and demands cooperation from all. The current use of engineered timber requires a near-complete design in terms of window openings, service penetrations and component size. This is due to the structural product being imported from Europe in shipping containers and taking 3-4 months from design completion until arrival upon Australian shores. Elements are fabricated in factories by computer-controlled machines and therefore require completed designs. Major design errors requiring rework would lead to lengthy supply delays that could hold up the building schedule.

This risk is not present in reinforced concrete structures that can accommodate late design changes with minimal impact on the schedule. The requirements of upfront timber design resolution also require a lot of coordination of designers to ensure that building services fit within the structure and fabric of the building and that no service clashes exist. Fire design is of particular concern to practitioners because tall timber structures are not currently compliant to existing codes so time and money are expended to provide testing and reports to achieve the satisfaction of regulatory authorities. Strategies have been suggested by practitioners to help overcome some of these challenges and concerns. These include having a local manufacturer of prefabricated timber elements, education of design practitioners about timber design and performance, and building code changes to reflect the current performance of timber in multi-storey buildings.

iii) Approval and tendering

Approval processes usually involves compliance with the National Code of Construction (NCC), Australian Standards, specific local or state development guidelines and certification by certifying authorities or private certification companies. Price negotiation for smaller residences generally involves a builder or volume building company/developer setting up a contract directly with a client (Nolan 2009). Multi-storey and large building developments involve a tendering process that is open or selected and based mainly on price. This process involves a main contractor (builder) getting prices from subcontractors (trade or manufacturers) based on contract documentation and places the contract risk on the bidders. Varying from the design specifications to propose differing materials or building systems in order to reduce price or add value is known as an alternate tender if it is additional to a conforming tender or non-compliant if it is the only tender. Suggesting the use of timber instead of the traditional materials specified would require a detailed knowledge by the tenderer of the characteristics and capabilities of timber.

There are no restrictions to the use of timber in small residential projects in terms of building codes and standards unless the property is required to be of fire resistant materials due to proximity to fire prone land (AS 3959). Volume homebuilders have their fixed design offerings based on traditional materials and efficiencies gained through repetitive work based on standard-size building elements and limited designs. This lowers the cost of material supplies and reduces time for trades people to complete their work.

Introducing timber designs into volume building would need to consider the impacts of changing building processes, supply chains and onsite practices. Multi-storey developments face different challenges to using timber through the approval process (as discussed by interview participants in using timber) as the building code does not permit timber in buildings over four storeys. Fire performance, as has been discussed already, and also structural performance require more time in design and approval processes. Convincing authorities such as the fire superintendent and building certifiers in addition to gathering technical evidence for approval and insurance agencies uses resources not always available to small and medium-sized building contractors and developers. This has limited recent timber structural buildings in Australia over four storeys to just a handful and these were completed by the larger building companies/developers.

Two additional issues were raised by interviewees regarding the tendering and trade procurement stage for timber structures. The first is the upfront payment for material orders for the structure prior to delivery and installation that could cause cash flow shortfalls for the main contractor. The second is the lack of competitive tenders for a structural timber installation trade package due to the lack of experience in this construction methodology. Solutions to overcome these issues need to include change of approvals processes, guidance for practitioners on contractual issues and education for current and future practitioners and trades on timber construction in tall residential buildings.

iv) Construction

Construction companies will often use subcontractors based on price and quality of installation and these builders will often be loyal to local material suppliers

(Nolan 2009). Construction programming in detached homes places some emphasis on time although there is generally flexibility in contracts for limited time delays. Larger multi-residential buildings, however, are more complex and require a wider range of building materials and processes. In these types of projects, project team performance has been flagged as a significant factor in time performance (Walker & Vines 2000). Time delays can attract liquidated damages and add cost to the main contractor in administration and site establishment (Eggleston 2009).

Time was not considered a significant feature in the responses from the homeowner survey of timber home construction although there is pressure on builders to complete housing quickly to limit onsite costs and improve cash flow and profits. Larger projects face a different scenario with site costs reported by interview participants ranging from $10,000-$100,000 per week. They suggested that the use of prefabricated timber structures have the potential to provide huge financial benefits by reducing the following time related costs:

- Structural erection time – fewer tradespeople and crane costs
- Amenities – fewer onsite personnel
- Truck movements – less vehicle movement supervision
- Safety – less supervision costs related to reduced number of trades and dangerous activities
- Building services installation – faster installation

Time reduction is becoming more important in construction projects and if these are achievable with the use of timber then it will become more competitive compared to traditional materials. This will need to be tested and confirmed through a number of successful projects and the data distributed amongst construction practitioners and developers.

v) Acceptance and occupation

This is the final stage and involves the client accepting the quality of the finished product and testing of building services has been completed. Once the works are accepted and certifiers have ensured the building is code compliant the client can occupy, lease or sell the building with warranty periods covering defective work appearing for an agreed time. These two final stages in the process don't allow for major changes in the design or material options so decisions must be made by the client at the outset of the project, through the initial design stage or at the latest during the tendering stage. Project costs are likely to increase if changes are made later in the procurement process than if they are made at the beginning.

In summary, the main barriers associated with increasing the use of timber in residential buildings identified for the construction procurement process include lack of information on cost and understanding of timber performance and the construction process. Time and scheduling issues also present a challenge to be overcome as along with the need to educate design professionals and other industry stakeholders in the performance attributes of timber. The challenges of complying with legislation and an absence of credit for using timber as a sustainable building product have been identified as additional barriers. Maintenance, durability and demolition are considerations, too, although developers consider these as issues of future building occupants and owners. Some of these factors will be discussed later in this chapter through the development of a strategy towards sustainable residential building. The misperception of timber performance will be discussed in the following section through a comparison between survey results, interviews and the literature about timber qualities.

7.3.3 Misperceptions of timber performance in residential development

Misperceptions of timber characteristics have been discussed in Chapter 3.3 along with research describing actual timber performance under circumstances such as fire, noise transfer, durability, insect attack and maintenance problems. The survey and interview results also discussed demand and supply side perceptions and misperceptions relating to timber performance in residential developments. Table 7.2 shows a summary of data results from the interviews and surveys alongside the literature findings to present a comparison between current perception and scientific research.

Table 7.2 Comparison of timber perception between literature and data results

Performance Attribute	Demand side Perception	Supply side perception	Reality	References/ Data
Fire				
Structural	Poor structural response	Poor structural response	Predictable/good performer in fire	Roos, Woxblom & McCluskey 2010 Sundkvist 2008
Connections	N/A	Challenge in design	Many options available	Mohammad & Munoz 2009 CLT handbook
Design	N/A	More costly and time consuming	True. Requires design resolution prior to material order	Data
Repair	N/A	Challenging to repair after fire	Easier than heavy materials	Data
Approvals	N/A	Time consuming and costly	Time consuming and costly	Knowles et al. 2010 Data
Acoustic				
Floor	Poor performer Allows thumping sounds from residence above	Poor performer Difficult to design to reduce low freq. sounds	More time for design. Many options available	CLT Handbook 2012 Baetens, Jelle & Gustavson 2011 Data
Walls	Allow sound to penetrate	Not a problem Easy to design	Simple design solutions	Multi-residential timber design guide 2012/Data
Insect				
Floor & wall	Poor performance	Concern with multi-residential developments	Timber treatments or Design solutions available	Crews 2003 FWPA 2011 Blue Pine 2014 Data
Durability				
Moisture	Rotting and decay	Poor performer in the presence of moisture	Modified timber Timber preservatives Design solutions	Rubik 2009 Osmose 2006
Maintenance	Costly and time consuming to maintain	Costly and time consuming to maintain	Requires high maintenance when exposed- compared to heavy materials	Gold & Rubik 2009 Papadopoulos & Pougioula 2010
Thermal				
Floor & walls	Poor thermal resistance High levels of infiltration	Good performance in solid timber sections	Dependent on good design, workmanship and insulation	CLT Handbook 2012 Data
Sustainability				
Product	Considered sustainable	Considered sustainable	Sustainable	Wagner & Hanson 2004. Data

Table 7.2 summarises the perception of both the supply and demand side of the Australian market towards some of the attributes of timber applied to residential development. The table also provides the reality of timber performance as reported from published investigations such as testing and data analysis. The difference between perception and reality is summarised in the following points:

- Perception of timber in fire is poor in relation to structural performance and repair in addition to being difficult through the design and approval processes. Whilst there are challenges in the design and approval phases, timber performs predictably in fire and is simple to repair.
- Acoustic performance is considered poor for floors and walls being not as resistant to sound transmission as heavy materials. Design solutions are available for both walls and floors although floors are more complex to construct to achieve acoustic compliance.
- There is fear of insect destruction of timber from both the supply and demand side. Design solutions are available and common and just require appropriate design and installation.
- Durability in the form of moisture damage and maintenance requirements is of concern to homeowners and construction practitioners. Products are available to protect and prolong the life span of timber and reduce maintenance costs.
- Thermal performance is considered poor by homeowners. Practitioners, however, view it as a good performer in large sections and the literature demonstrates that timber is thermally efficient in large sections and with lightweight framing when designed with appropriate insulation.
- Homeowners and practitioners both agree timber is a sustainable product. Homeowners would pay more for timber as a sustainable material yet practitioners believe it is more expensive and provides no return or credit under current legislative requirements. This is the current reality for Australia's residential construction market.

A number of misperceptions about timber performance exist among homeowners, designers and suppliers respecting residential developments. These considerations along with barriers discussed in the previous section could explain the persistence of the use of heavy materials. The following section looks at detached residential development and identifies the current development model and how this model hinders the use of sustainable materials. The section then proposes a sustainable residential development model to overcome the barriers and challenges to increased sustainable material uptake in residential development in Australia.

7.4 Improving sustainability in residential development

Chapter 2.3 examined current efforts in the construction industry to reduce environmental impacts through the use of operating energy reduction strategies. That section revealed that embodied carbon was increasingly pertinent to sustainability and suggested that the increased use of timber could assist in reducing the carbon impact of the residential building sector. This section maps the current residential development model and shows that it is focused on delivering housing to achieve profits for the supplier and value for the home purchaser in the form of a value for money, quality, and packaged service. The discussion also proposes a sustainable model that incorporates all the offerings of the current model in addition to reducing carbon impacts on the environment via a life cycle perspective.

7.4.1 Current Australian residential development model

As discussed in Chapter 3.2, concrete floors and brick veneer are standard practice for detached homes (IBIS World 2011). The basis of the development model for residential homes in Australia for many years has been low cost, packaged solutions in which companies provide limited design options and the customer pays for a completed product on either their own land or the land owned by the company offering the set design homes (Sommer 2010). The reason for some of the cost savings in these packaged (also known as turnkey) projects is found in the list below:

- Fixed design – changes will be charged to customer at a premium
- No architect required – design cost for a particular model is spread over a number of projects.
- Basic design is usually based on a simple 'slab on ground' footing – steep or difficult sites attract additional costs
- Designs are created for maximum material efficiency (room size/floor-ceiling heights/truss design)
- Fixed labour and material supply agreements
- Repetitive work for subcontractors allowing for time efficiencies
- Reduced amount of building supervision – repetitive work for subcontractors means less supervision/instruction is required.
- Designs suited to comply with local council regulations without alteration, which allows for a quick approval process.

Built to order homes cannot achieve these same efficiencies as they attract greater design fees, have bespoke structural designs and don't have the same labour or material efficiencies built into the design. In the Australian residential market there is a lack of research into incorporating sustainability into residential construction models so a representative model has been developed from values, mission statements and objectives of 32 residential developers in NSW. Table 7.3 displays elements of the customer value proposition by 32 volume homebuilders and their mission/aims/objectives. These were derived from their websites and from this information a current business model is established to represent their business activities.

Table 7.3 Summary of client value propositions from residential developers

Residential Developer	Company values listed on websites	Price Value	Upgrade option/ package	Year Estab.	Time	Environment/ social
Alkira	Highest Quality	✗	✓	1970's	✓	No
Allcastle	Affordability	✓	✓	N/A	✗	No
Allworth	Reputation/ Quality	✓	✓	1978	✗	No
Beechwood	Quality / service	✓	✓	<1984	✗	No
Boka-Krslovic	Quality/ innovative	✗	✗	1971	✗	No
Casaview	Quality & expertise	✓	✓	1994	✗	Charities
Charleston	Prestige	✗	✗	1990	✗	No
Clarendon	Award winning/ trust	✓	✓	<1984	✗	Eco upgrade/ operation energy
Daleth	Quality/ luxury	✗	✓	1979	✓	No
Eagle	Quality/ service	✓	✓	1984	✗	No
Eden Brae	Service/ quality	✓	✗	2000	✗	No
Ferntree	Unique design/ quality personal service	✓	✗	1994	✗	No
Firstyle	Quality/service	✓	✓	N/A	✓	No
Fowler	Sophisticated designs/ quality /service	✓	✓	1978	✗	HIA GreenSmart / local charities
Huxley	Quality/range/ customer service	✓	✓	<1970	✗	No
Ichijo	Premium energy efficient	✓	✓	Japan <1980 Sydney 3 years	✗	6-8 star NatHERS green options.
Kurmond	Quality/custom	✓	✓	1994	✓	No
Lifestyle designer	Architectural excellence/ service	✓	✓	1980's	✗	No
Lily	Dreams into reality	✗	✗	<1990	✗	No
Masterton	Excellence	✗	✓	<1965	✗	No
McDonald Jones	Trusted/ commitment	✓	✓	1987	✗	McDonald Jones Charities
Merit	Unique and challenging designs	✗	✗	<1984	✗	No
Metricon	Customer first/quality excellence/ innovation	✓	✓	1976	✗	Brick/hebel energy efficient
Montgomery	Quality and integrity	✓	✗	1989	✗	Greensmart/ greenfleet
Morrison	Luxury and quality	✓	✗	N/A	✗	Sust. Inclusions
Provincial	Attn. to detail	✓	✗	1990	✓	No

Residential Developer	Company values listed on websites	Price Value	Upgrade option/ package	Year Estab.	Time	Environment/ social
Rawson	Quality & service	✗	✓	1978	✗	Sust. design
Sarpel	Prestige/ quality	✓	✗	N/A	✗	No
Sekesui	Innovation/ quality and sustainability	✗	✓	1960 Japan. 2009 Sydney	✗	HIA GreenSmart / green options
Wincrest	Excellence/ quality	✗	✓	1986	✗	No
Wisdom	Innovative/ attractive	✓	✓	1999	✗	No
Zac	Builder of Distinction	✓	✓	<1992	✗	Charities

Source: Homebuilder websites of each homebuilder listed in the table

Table 7.3 represents residential developers' client value propositions and includes values such as key company purposes, mission and vision. It also includes their years in business, value for money, time performance and sustainability. These aspects of value offerings were chosen as they make up the critical success factors of construction projects as well as being the basis on which many building companies attempt to differentiate themselves from their competitors. Each of these factors is discussed separately below.

- The key company values were compiled from the mission statements, company mottos, and vision of each company. These included phrases such as integrity, honesty, personalised service, dedication to the client, prestige, luxury and reliability. The majority had quality as one of their main company characteristics and this is one of the four performance indicators for construction projects as identified in Chapter 2.5.
- The second and often the most critical project performance indicator and selection criterion most often used by customers is cost. Companies used a variety of terms to indicate their financial value proposition including affordability, value for money, cost competitiveness and cost efficiency. There were 68% of companies that had claims to this effect on their websites.
- Time performance, which is closely linked to cost in most construction projects due to loan interest, opportunity cost and loss of rental income, is

also a performance indicator in construction projects. Only five of the 32 companies searched discussed time element in statements such as being efficient in planning and building and commencing within certain time frames. Only three companies provided an actual build time or guaranteed that time frames would be met. Despite the lack of emphasis on the importance of time by homebuilders, it is recognised as critical in the literature and the perspective of construction professionals interviewed.

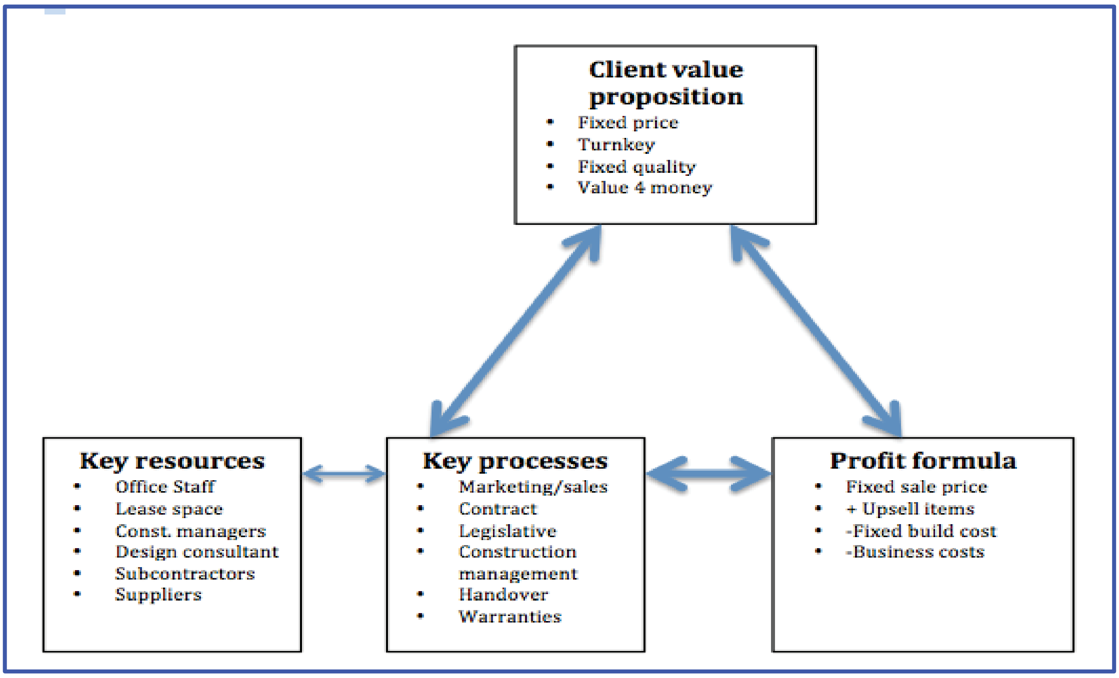
- Three companies offered sustainable upgrades that included features such as greater insulation, photovoltaic systems and double-glazing, which are all based on operating energy. There were claims of using sustainable materials such as aerated concrete and brick, involvement with sustainable design and having sustainable accreditation with building company associations. This was not represented as a critical factor in the client value proposition from homebuilders despite being flagged as an increasing obligation for the construction industry as discussed in Chapter 2.5.

Time, cost, quality and sustainability performance have been identified in the literature as being critical elements in construction project success (Gilchrist & Allouche 2004). Interviews and surveys have also verified that these elements must be addressed for sustainable material to be used as an alternative to concrete and brick construction in residential development. Client value offerings by residential developers identified in Table 7.3 indicate that, for volume builders, cost and quality are the main focus with time and sustainability having less importance. The following section describes the current model that represents the operations and client value offerings for residential developers based on the typical concrete and brick residence.

7.4.2 A representation of the current model for residential buildings

Figure 7.3 is representative of the client value proposition model for residential construction companies that is based on Carroll's (2012) typical business model and adapted using client value propositions found in Table 7.3.

Figure 7.3 Residential development client value proposition model



Source: Adapted from Carroll 2012

Figure 7.3 includes key resources, key processes, client value propositions and the business profit formula. These are explained in greater detail in the next subsections.

i) Client value propositions

The value proposition for clients in these residential development projects includes a fixed price, turnkey solution, fixed quality and value for money. The benefit for many customers of turnkey solutions is a fixed price for a new home build that includes all the processes required for construction from signing the contract until handover of the finished project. Fixed price reduces the risk of budget overruns and predetermined quality removes one area of dispute from the contract. Display homes allow clients to view a representation of the finished product that construction drawings or computer simulations don't provide. The other value proposition for clients in current residential projects is the perception of value for money compared to an individually designed residence.

ii) Key resources

Key resources for residential development include business management, office administration and sales and construction project management staff. Consultants can include engineers, architects, surveyors and private certifiers and the larger companies may employ their own design staff. Project managers manage trade labour and material suppliers.

iii) Key Processes

Residential builders offer turnkey solutions to customer and will take care of the entire process from council approval to completion. Contracts are signed, and soil testing, site surveying, and engineering design are completed and plans are submitted to legislative authorities. Construction is managed by the project manager who engages suppliers and subcontractors to complete the work and ensures that quality and schedules are according to the contract. The building company completes handover and defects are resolved and the warranty period commences.

iv) Profit formula

The residential building projects are based on set designs, agreed contract prices for suppliers and subcontracts and efficient processes, so there is a high element of predictability in the profit margin for each project. The unpredictable costs mainly reside in the staff costs, leasing space, and marketing departments. The main risk for volume builders is a lack of volume in sales that can be affected by both industry economics and the market share that each company holds.

In summarising the current residential business model, it offers cost and quality benefits to customers and profit for the residential developer but fails to address the sustainability aspects of residential project performance. The current sustainability options of the current model are limited to upgrades and inclusions based on reducing operating energy such as photovoltaic cells, solar hot water and increased insulation (Table 7.3). As legislation places greater obligations on builders to meet sustainability targets, companies will need to incorporate strategies and adjust their business models so they remain competitive in the coming low carbon economy (Galharret & Wang 2011). Other reasons to increase the adoption of carbon reduction for residential construction companies include the following:

- Reducing carbon can increase their reputation in the industry (Hoffman 2005; Rao 2002)
- Clients are increasingly requiring contractors and associated suppliers and consultants to adopt sustainable practices (Tan, Shen & Yao 2011)
- Improvements in sustainable performance can have a large influence in construction company competitiveness (Shen & Zang 2002; Tan, Shen & Yao 2011). Four sustainable strategies were devised by Orsato (2009) that when applied to the residential building process could create competitive advantage

    - Eco efficiency – Optimisation of current processes e.g. reduction of the amount or weight of materials and a reduction in workforce or time for construction
    - Environmental cost leadership – providing lower cost homes with lower environmental impacts
    - Beyond compliance – leadership going beyond current environmental legislation. e.g. reduction of the embodied energy in new homes through the use of timber over heavy materials
    - Eco-branding – Use marketing to educate customers of the differentiation in environmental business models between companies

In the development of a sustainable development model for residential construction it is important to incorporate the sustainable criteria discussed in Gilchrist and Allouche (2004) into the new paradigm for sustainable construction discussed in Figure 2.3 of Chapter 2. The sustainable aspects presented by Gilchrist and Allouche (2004) emphasise the reduction of use of natural resources, minimising environmental impact and accounting for the use of energy throughout the life cycle of a construction project. The current residential model only partly looks at reducing environmental impact through operating energy and fails completely to incorporate embodied energy reduction through the use of sustainable materials. The current model is also based on the use of finite resources and so fails to minimise resource consumption in residential construction. Finally, the current model does not consider the end use of the material cycle through the life cycle of a residential building.

7.5 Developing a sustainable building model for residential development using renewable resources

Discussion in this chapter has so far identified the stakeholders and interactions of stakeholders in the construction industry according to Seaden and Manseau's (2001) framework for analysing innovation systems in construction. It has also discussed the stages of Australian residential building at which major changes in materials and processes can be introduced. The discussion has also compared the barriers and challenges to timber construction with the benefits of implementing timber into the procurement process. These barriers, challenges and benefits were sourced from the literature and data collected in the interviews and survey as part of this research.

Interviews of construction practitioners demonstrated that, from the perspective of developers and builders, timber construction needs to be cheaper and quicker to build, and as durable as conventional materials. Sustainability in the form of carbon reduction benefits were viewed as beneficial, but only considered after cost, time and quality attributes. Survey data showed that homeowners accept that using timber will lessen the impact of carbon on the environment compared to traditional materials yet had fears of maintenance and durability performance. Information from residential developers was used to present a client value model. This model showed that the offerings were based on cost and quality with less emphasis on time, and sustainability was limited to a focus on residential operating energy. The following models show, firstly in Figure 7.4, the traditional model of residential construction based on a typical procurement process. The second model (Figure 7.5) presents a cyclical procurement process with the introduction of timber as a substitute for traditional materials in order to decrease carbon impact, reduce the depletion of natural resource stocks and increase the reuse of materials in addition to bringing time, cost and quality benefits to the building's life cycle.

7.5.1 Linear model versus life cycle model

The current residential development model is a linear model as it starts with the selection of a fixed design option and is completed once the building is constructed. The developer completes initial approvals and construction is undertaken according to the contract. The operation and maintenance of the building is the owner's responsibility for the typical life span of 50 years. Demolition and waste disposal is also abdicated to the owner and is therefore not a significant concern of the developer. The end of the life of the building is site clearing that allows the cycle to recommence. The material life cycle is shown in Figure 7.4 and commences with the client's choice of a particular design and its associated aesthetic finish. Heavy materials dictate traditional design with the use of reinforced concrete floors, brick or aerated concrete panels for external walls and finishes such as cement render.

The approval process is simple due to the existing building codes that permit the use of reinforced concrete and brick envelope without any further testing or justification (BCA 2013). The only additional design required is the structural engineering details that are required for the concrete floor slab. Waste materials from structural construction activities include timber frame offcuts, concrete, bricks, and reinforcing steel offcuts. These exit the material cycle with the majority going to landfill or recycled for use into lower grade products such as road base (Crowther 2000; Australian Government 2012). This is a similar scenario for materials separated from the demolition process. Landfill is the final destination for the waste items from the renovation and maintenance activities during the building's operation. Figure 7.4 shows the residential material flow during the residential procurement process.

Figure 7.4 Traditional residential procurement model with linear material flows

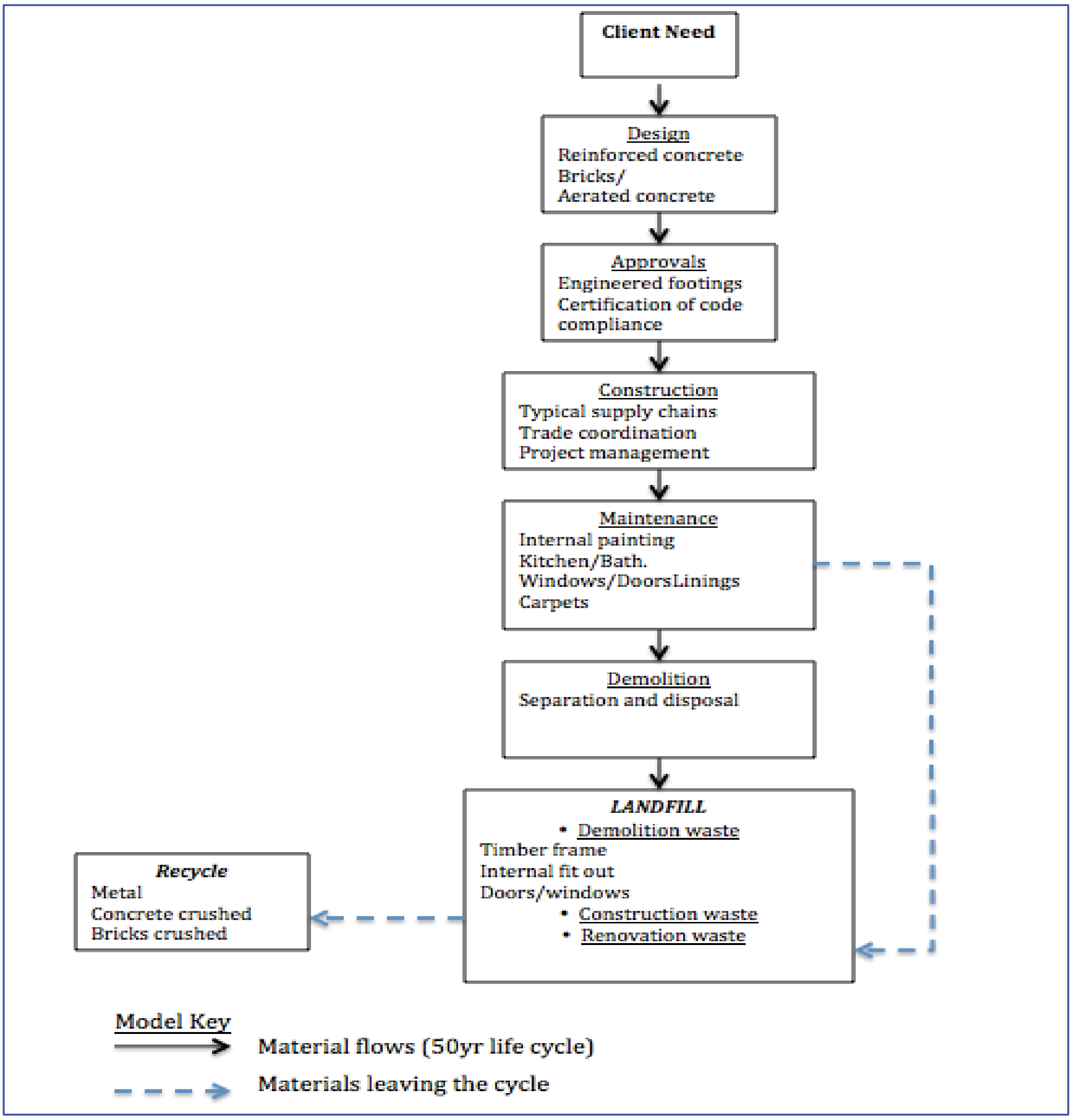


Figure 7.4 shows the material flow of the traditional residential development project, which is considered a linear approach. This approach contains a number of issues regarding the reduction of carbon impact through its life cycle. In terms of design there are limited opportunities to introduce systems that allow for disassembly or reuse. Reinforced concrete poured in place, the current method

of flooring, inhibits the opportunity for prefabrication efficiencies in time and costs. Reinforced concrete is also high in embodied carbon and uses non-renewable resources. It also requires a lot of energy during the demolition and transportation to recycling or landfill. Reuse is only possible after crushing into gravel size pieces for use in other products or as subgrade material for roads. Bricks are not designed for reuse due to the current procedures for installation. Bricks also use a non-renewable resource, require high energy to produce, are time consuming to install and do not currently benefit from prefabrication. Reinforcing steel is embedded in concrete, is produced from finite materials, is high in embodied energy and is demolished using destructive machinery. It does, however, have the capacity to be recycled into reinforced steel through a high energy consuming process.

This current model is considered to be model as it only considers the process up to the point where the building is complete and this is the objective of the whole project. This perspective is in stark contrast to the principles of life cycle thinking and the concepts of sustainability addressed in Chapter 2.2. The issues with a linear approach to residential building will now be applied to the residential development construction process.

The design phase in residential development is critical in selecting the materials for a project. The building layout, building footing, structure and thermal calculations are all dictated at this stage. The current model is dependent upon heavy materials and the designs are created to gain cost efficiencies from these materials in order to produce the greatest profit. Insufficient consideration is given to the cost of operating the building, ongoing maintenance or the end of life phase of the building. The environmental affect of using finite resources is also not considered in the design phase of the project.

Volume builders have a range of set designs that have shown to optimise the approvals process by complying with the building code in regard to structure, thermal performance, lighting, ventilation, and other requirements. The building codes do not currently require minimum life cycle performance standards for building operation, maintenance, or demolition in regard to cost, quality and sustainability. This allows developers to pursue minimum building performance over its life span and maximum profits for the construction phase. Using heavy materials currently limits reuse of materials beyond the life span of the project. Reinforced concrete is poured in place; bricks are laid with non-removable mortar; and both processes neglect the possibility of material reuse and do not consider the final destination of the materials. The end of life scenario in this linear model is destructive demolition that prevents reuse without a high-energy intensive process resulting in recycling into poor quality products or landfill.

In summary, the current linear approach to residential development using heavy materials limits sustainability in building projects and focuses on profits from the construction phase of home building. The ongoing costs of maintenance, energy and demolition/disposal are passed to the owner and the energy burden of all building life stages activities is carried by society. The consumption of finite resources is also a mark of this linear approach to residential construction. In addition, the traditional residential construction model is based on heavy materials that restrict efficiencies and sustainability through the following aspects:

- High levels of on site labour (wet trades)
- High embodied energy materials
- Destructive demolition required for recycling or transportation to landfill
- High energy required for recycling
- Use finite resources for production

The following section introduces timber as an alternative material to reduce carbon impacts on the basis of a circular material flow that allows for disassembly, reuse or recycling to its original on site construction purpose. The importance of introducing a cyclical model is that it accounts for the entire energy and cost of the building from its conception to its termination.

7.5.2 Timber residential procurement cycle model

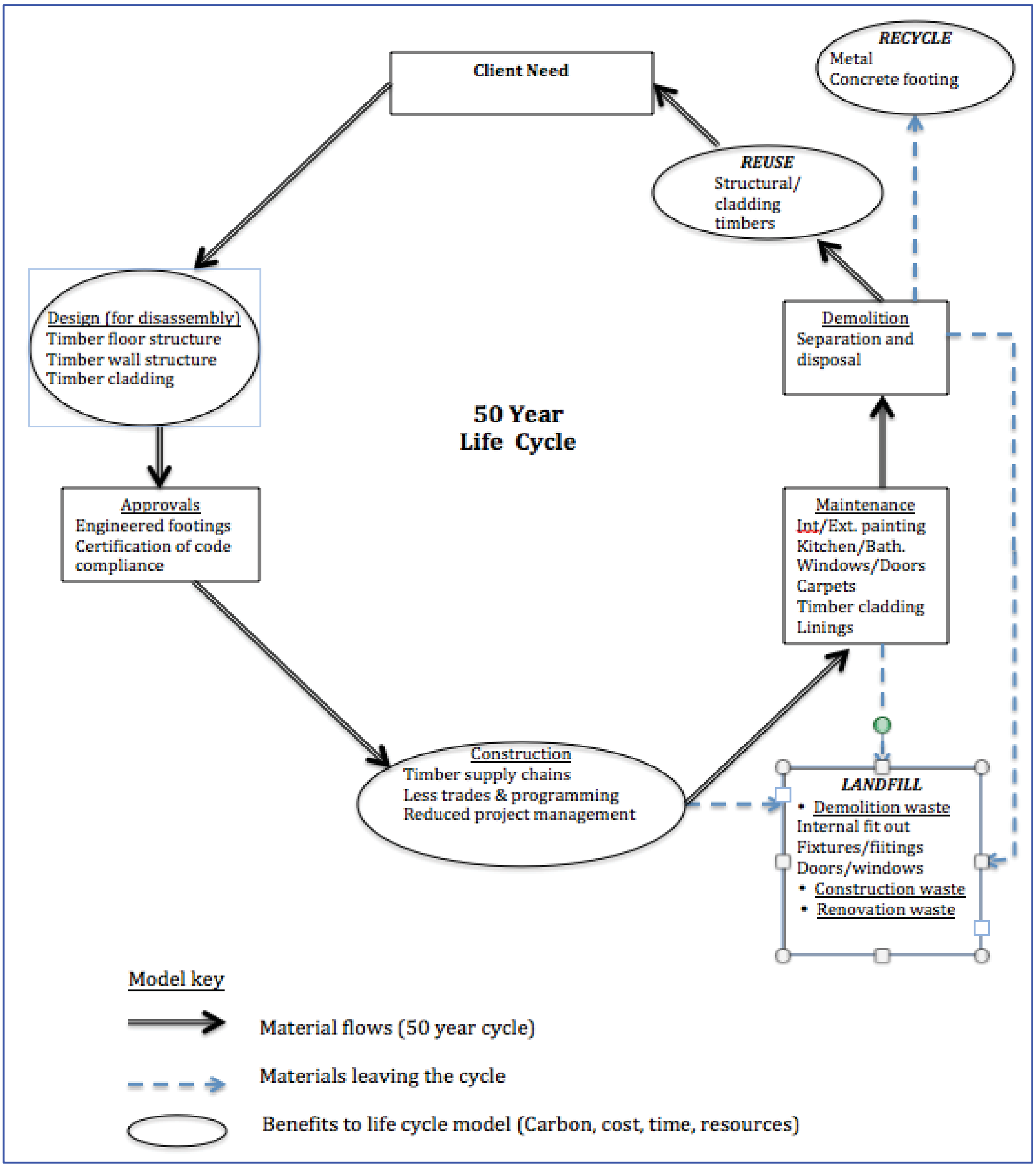
The procurement cycle for a timber residential project is similar to the traditional model although a sustainable residential model needs to be cyclical to conform to the current broader concepts of sustainability and to address the obligations of the construction industry to reduce its impact on the environment. Energy flows in a building through its life include the conversion of raw materials to building products, from building products to complete buildings, operational energy, and the demolition and end of life disposal, reuse or recycling. The importance of a life cycle measurement of energy and costs is that it places significance on the selected materials incorporated into the project at the initial stages of design.

At the design stage, timber designs need to be produced by the developer and be made available to the client as a carbon reduced sustainable housing option. The design will also need to be designed to plan for a closed loop material cycle by considering disassembly at the end of the timber structure's life span. A similar approval process to the traditional model will be required regarding building code and BASIX compliance although the requirement for engineer structural design may be reduced if the design complies with the Australian timber framing code (AS 1664, 2010).

The construction phase will reduce the number of onsite trades due to eliminating the concrete and bricklaying trades. This will allow for efficiencies through the use of carpentry as the main trade on site to reduce construction time and on site supervision and trade coordination. Cost reduction can be achieved through material supply agreements due to increased utilisation of a single product for the housing structure. Procurement processes by the developer will be required to accommodate the change in construction programming to gain maximum time efficiencies by using the timber procurement model.

Maintenance will be greater for the timber model due to the requirement of replacing timber cladding half way through the building life cycle in addition to painting of the cladding (Osmose 2006). This adds costs to the timber model although gains carbon reduction benefits with the storage of carbon remaining in the timber cladding in landfill (Ximenes & Grant 2013). Demolition is cheaper for timber residential buildings due to reduced excavation equipment use and reduced waste disposal costs related to the low weight of timber compared to concrete and brick (DECCW 2010). In the worst-case scenario that the timber is landfilled, the majority of the carbon stored in the timber products remains and therefore benefits the timber building in its life cycle (Ximenes & Grant 2013). If timber is designed and used to cater for a disassembly and reuse process, benefits could be brought to the building cycle through reduced resource use, cheaper materials and lower carbon impacts through manufacturing and production offsets (DECCW 2010). Figure 7.5 displays a cyclical material flow in the proposed timber residential procurement model.

Figure 7.5 Timber residential procurement model with circular material flows



In the model in Figure 7.5, the material flows for timber demonstrate the potential for reuse in future projects. This is dependent upon the consideration of the end of life scenarios for materials during the design phase of the procurement process. The construction phase proposes time savings in the building erection and reduced time and cost required for project management related to a reduction in trade coordination and time on site. Maximising reuse of timber products could provide cost reductions in the form of reduced waste disposal charges and avoided costs for future project materials. This type of circular thinking is not yet common in residential development and may take some time to implement once it is demonstrated to provide benefits to developers, clients and the industry. However, the increase of timber use in residential development can be considered as an initial strategy to reduce cost, time, and carbon impact in addition to increased quality in the form of thermal performance. The following section explains how performance criteria were chosen to develop and test a sustainable residential development model.

7.5.3 Developing a sustainable model for residential development

The use of timber in residential developments is considered to be a sustainable development option as identified in the literature, questionnaire survey and interview data. Perceptions of timber were both positive and negative with some perspectives matching up to data on timber performance and others based on previous bad experience or misperceptions. These perceptions are listed in Table 7.4 and have been separated into positive and negative attributes of timber.

Table 7.4 Classifying timber perceptions into positive and negative attributes

Perceptions of timber performance	
Negative	**Positive**
Poor performance in fire	Sustainable
Structurally inadequate for residential construction	Faster structural construction
Poor acoustic performance	Easier material handling
Poor durability	Less labour required
Destroyed by insects	Carbon sequestration
Rots when exposed to moisture	Decreased overhead costs
Requires too much maintenance	Less site supervision
Poor thermal performance	Faster services installation
Requires longer for design (multi-residential dwellings)	Less waste
	Renewable material
	Less embodied energy

These perceptions of the attributes of timber have been grouped under categories in Table 7.5 that best fit the measurable performance criteria. Time, cost, quality and sustainability are the four major criteria used for the reason that they are typically known as critical success factors in construction projects as discussed in the literature review found in Chapter 2.5.

Table 7.5 Classifying timber perceptions into performance criteria

Time	Cost	Quality	Sustainability
Fast construction	Less construction waste	Poor fire resistance	Renewable material
Fast service installation	Less site supervision	Poor acoustics	Carbon sequestration
Longer lead times	Reduced labour	Structure concerns	Greater sustainability
Reduced crane time	Decreased overheads	Poor durability	Less embodied energy
Increased design resolution	Reduced disposal costs	Moisture damage	
More design coordination	Increased maintenance	Insect damage	
Less change flexibility	Greater design cost	Poor thermal comfort	
	Increased sustainability costs		

Table 7.5 groups perceptions from interviews and questionnaire survey data into construction performance criteria. They include perceptions of both construction practitioners and homeowners and include both detached residential and multi-storey timber projects. These broad performance criteria of time, cost, quality and sustainability have been organised into subgroups to assist in the identification of criteria to be included in the development of a sustainable residential development (SRD) model. Figure 7.6 displays a sustainable model for residential development and the model was divided into four main criteria and each main criterion was further subdivided into sub-criteria.

Figure 7.6 Sustainable residential development (SRD) model

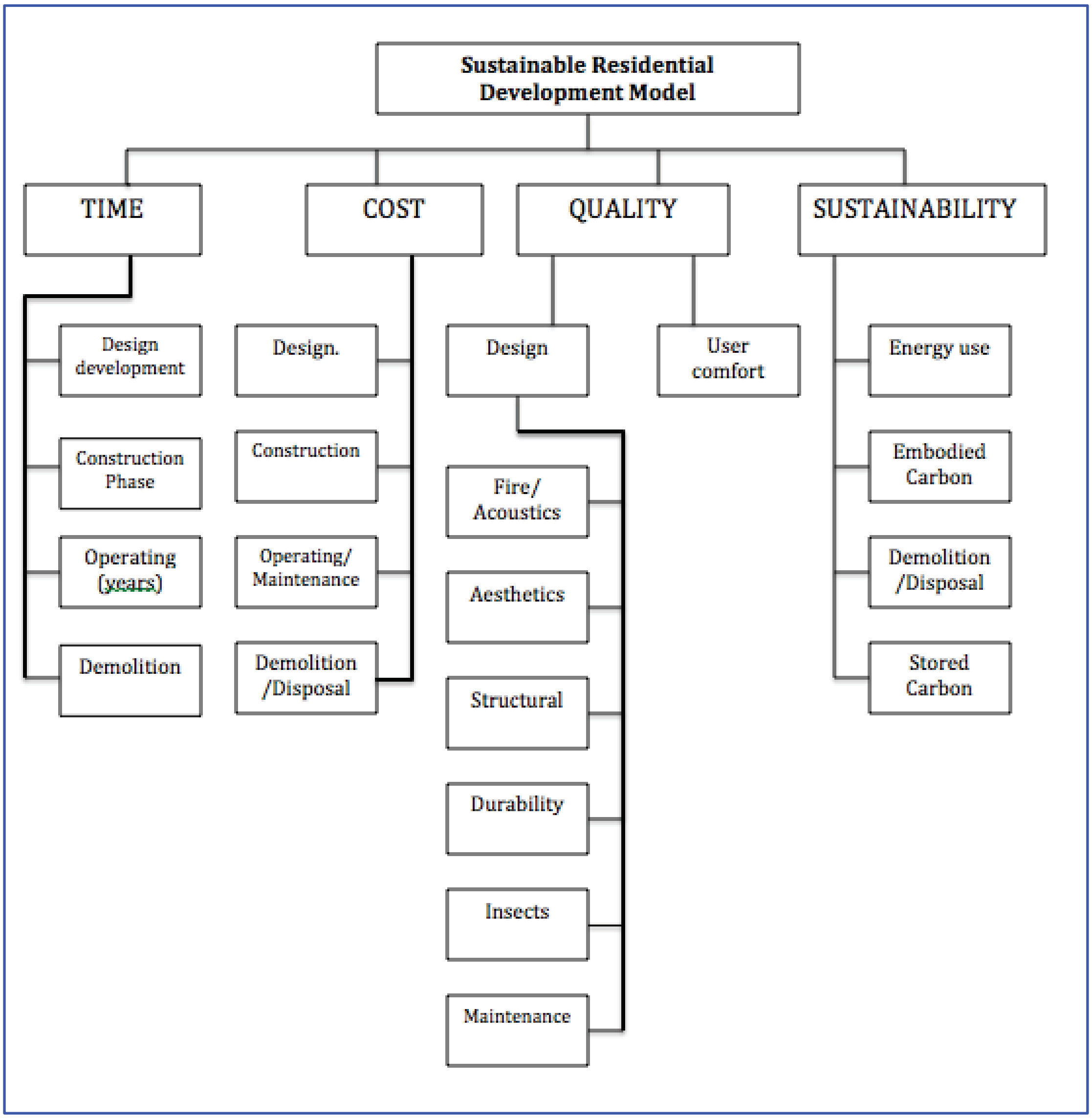


Figure 7.6 shows the demand and supply side perceptions of timber gathered from data analysis combined with the literature to develop a sustainable residential development (SRD) model. The model amalgamates time, cost, quality and sustainability into a single assessment model on a life cycle perspective. This approach is different from the current linear model in that it considers upfront costs and operating and maintenance costs in addition to the end of use cost. The current model does not consider the end of life cost and only addresses the operational costs if that is required by regulations or provides a marketing advantage for the developer. The current linear model is mainly concerned with the upfront sale price.

The SRD model also addresses time performance in the construction phase and end of life phase by creating efficiencies that benefit the home occupier both in the short and long term, and also provides economic advantage to the developer in the short term. The linear model is currently serving just the immediate benefit to the developer by producing savings and improved cash flow with limited concern or interest for the home purchaser. The SRD model considers the final destiny of the materials used in construction at the outset of the building project as well as the maintenance and end of life stages. It aims to reduce the energy use in the material production stage, operating and maintenance stage and the end of life stage. The linear model only pursues energy reduction in the operating stage. Timber is considered a suitable test case material to fulfil the objectives of the sustainable residential development model and to compare it to the current heavy material linear model.

Table 7.6 summarises the attributes and identifies those chosen for measurement to aid in the testing of the sustainable residential model through a case study comparison in the next chapter.

Table 7.6 Criteria chosen for case study testing

Perception of timber attribute	Previous testing of attribute completed	Is the attribute proven or a misperception	Identified Measurable criteria?	For use in case study?
Poor performance in fire	Yes	Misperception Academic studies available	Yes. Timber Charring times	No
Poor acoustic performance	Yes	Misperception Academic studies available	Yes. High and low frequency sound tests	No
Structural performance issues	Yes	Misperception Design & codes available	Yes. Engineering testing	No
Longer approvals process	Yes. Private company IP.	Perception based. Information unavailable	Yes. Approval time	No
Longer design times	Yes. Private company IP.	Perception based Information unavailable	Yes. Design time	No
Quicker construction time	Yes. Private company IP.	Perception based Information unavailable	Construction program	Yes
Poor insect resistance	Yes	Misperception Building code requirements	Insect resistance	No
Poor moisture resistance	Yes	Misperception- Building code requirements	Absence of rot	No
High maintenance costs	No	Perception based	Life cycle costing	Yes
Poor thermal comfort	No	Perception based	Thermal modelling	Yes
Cheaper life cycle costs	Limited	Mainly perception based	Life cycle costs	Yes
Reduced embodied energy	Yes	Proven	Life cycle Carbon accounting	Yes
Carbon sequestration	Yes	Proven	Life cycle Carbon accounting	No

Table 7.6 displays the criteria chosen for the case study comparison to test whether timber can improve the issues of the current linear heavy material residential development model that focuses on time, cost and quality to the detriment of sustainability. The purpose of the comparison between brick veneer and timber homes is to establish whether a home built of timber floor, wall and roof structure with timber cladding can compare with the typical brick veneer homes based on time, life cycle cost, thermal performance and sustainability (life

cycle energy). This will test if the cyclical approach to residential development outperforms the current approach that uses heavy materials. The particular performance aspects based on the sustainable residential development model Figure 7.6 are discussed in more detail in the next section.

i) Quality

Quality attributes are split into design based criteria and user comfort. The design-based criteria cover both building code requirements and particular aesthetic needs for particular projects. User comfort is represented by thermal comfort, as this criterion was a major concern among homeowners regarding timber when compared with heavier materials.

The quality of building is firstly dictated by the building codes and minimum standards and secondly on the preference of the client/developer. Structural capacity, durability, insect resistance and acoustics are all subject to appropriate legislative regulation and are required to be signed off as having complied with the minimum requirements. Aesthetics is not considered measurable due to its subjectivity and its dependency on client taste, end use market and locality of the building.

Thermal performance of timber has been identified as an issue in residential detached dwellings according to the survey and interview participants. Most survey participants indicate they perceive timber homes to be less comfortable in extremes of temperature when compared to heavy material dwellings. This aspect of quality is identified as a criterion to measure when comparing timber against heavy materials as it affects construction costs, time and operating energy costs. Thermal performance will be assessed by using energy simulation software such as AccuRate to produce a projection on heating and cooling. This aspect of user comfort is critical to operating cost as the use of heating devices and cooling equipment to achieve thermal conditioning in homes requires high levels of energy, particularly in the middle of the winter and summer. Building envelope design plays a critical part in providing protection from external temperatures and maintaining internal temperatures of homes. Therefore it was deemed critical to design the timber material used in the model to achieve equal thermal performance to those used in the current linear model.

ii) Time

Time is separated into the design development phase and construction phase. These were both mentioned in the interview responses and have received little attention from previous research on timber residential development.

Time in residential development can be measured in four main stages. These are the project initiation, design, construction and finalisation (handover and defects liability period). Life cycle time would include operation and end of life stages. Initiation and design stages involve a lot of variables not measurable due to the reliance on a range of government and private certifying and approval authorities. The operating stage of residential buildings is related mainly to the daily activities of the homeowner. Therefore the time involved in this stage is largely the same for any type of construction. The time for the end of life stage for the timber is currently shorter for timber homes compared to heavy materials built 50 years ago. The proposed current timber designs will not be able to be tested for 50 years and will be dependant largely on the legislation surrounding non-destructive demolition and material reuse. These stages are less important and therefore will not be included in the sustainable residential model. Construction time is tested as it has a significant impact on project cost and the use of human resources and building fabrication. The construction process and its affect on time is discussed in greater detail in the following subsections.

During construction, trade management is the organisation of all the specialty labour services required to construct a residential building. As the number of trades increases, so does the risk of losing time due to imperfect trade coordination and overlap. Efficient material supply and handling requires reliance on suppliers delivering the required materials in time for use on the project without having to be stored on site for excessive periods. Late deliveries can hold up the installation and delay construction. Whilst early delivery on site may ensure availability for installation, there may be limited storage space and there is a greater risk of weather exposure, damage or larceny and impact on cash flows.

Decreasing the number of trades on site reduces risks of material deliveries being late. Material handling on site can also be simplified by reducing the demand from multiple trades. Lighter and cheaper material handling equipment is required when using timber as compared with concrete and brickwork.

Service installation was identified in the interviews as being quicker and cheaper in timber structures when compared to concrete and masonry. Site operations are simplified in aspects of staff supervision and amenities requirements for the use of timber due to reduction of trades such as form workers, steel fixers, concreters and bricklayers. This reduces time for structural installation and a decrease in the overall construction phase.

The construction phase time is commonly calculated using the critical pathway method. This method identifies the activities that need to be completed on time to avoid holding up the project. This method sums up all these critical activities to identify the optimal completion time for a particular project (PMI 2013). This method will be implemented to measure the time of construction for the current residential project and compared to a sustainable timber residential project. Microsoft Project is the computer software that will be used as the measurement tool for the case study projects. This will take into account the standard times for particular trade activities in the industry as provided by industry bodies and experienced industry professionals.

iii) Cost

Cost will be assessed in a life cycle perspective that will include cost of design, construction, operation and maintenance, and end of use scenario. Design and construction costs were reported as the main focus of comment from this studies' investigation although operation and demolition were also discussed by a few practitioners when considering a life cycle cost perspective during their interviews.

Life cycle costs have four main identified criteria according to the sustainable residential development model in Figure 7.6. These are the design, construction, operating, and end of life costs. Construction cost will include site ground works and retaining structures necessary for protecting the structural integrity of the building's foundation. It will also include the building envelope structure and internal linings. Fittings and fixtures and services will be omitted, as they are the same in timber or heavy material dwellings.

Operating cost includes ownership and maintenance cost during the service life span of the building. Ownership cost includes utility bills such as water, electricity, gas and council rates. It also includes minor maintenance such as light bulbs and other consumables. Therefore it should be the same in spite of materials structure if thermal performance is the same. On the other hand the cost for providing heating and cooling will be largely the same for any materials structure. Therefore construction cost plays a more important role in comparing life cycle costs of homes built out of different materials.

Maintenance is required during the service life span of a building and the maintenance requirement will depend on the type of materials used. For example, it would be greater in a timber-clad residence as it requires painting and replacement at more regular intervals than brick veneer properties. Therefore the cost of maintenance and refurbishment is included in the life cycle costing.

In measuring the life cycle costs in the model for the timber buildings and heavy material projects, the formula presented by the Commonwealth of Australia (2001) in their guidelines for LCC is recommended. This formula is presented below:

$$LCC = CC + LTOC + LTMC + DC - RV \quad (1)$$

Where:
LCC = Life cycle costing
CC = Capital costs
LTOC = Lifetime operating costs
LTMC = Lifetime maintenance costs
DC = Disposal costs
RV = Residual value

Capital cost is in today's value (PV) and future costs are calculated into today's value by applying the net present value formula.

$$NPV = \sum_{i=1}^{n} \frac{C_i}{(1+r)^i} - C_0 \quad (2)$$

Where:
C0 = Initial investment
C = Cash flow
r = Discount rate
i = Time
n = Life of project

LCC is adopted for the economic analysis in this research based on the discussion in Chapter 4.3. The monetary value of cost will be analysed in each stage. In assessing the economic criterion only the costs are measured in the four stages of the building life cycle. The discounted cash flow approach is used to calculate money value in the economic life span.

In conducting the discount cash flow approach, the discounted rate needs to be determined in accordance with the market economy. Neale and Wagstaff (1985) conducted research into discounted cash flow and life cycle costing for construction projects in the UK. The different discounted rates of 10%, 20% and 30% were used to test the sensitivity of the results to the rate chosen. Ding (2005) also used three discounted rates 5%, 10% and 15% to conduct the sensitive study to analyse a project's different design options. Ding and Shen (2010) use the discounted rate of 5% to analyse the economic criterion of a 40-year life span building. In this research, the discounted rate is based on the market condition by taking into consideration inflation, loan on investment, etc., and a discount rate of 5% is used for the study.

To calculate the cost of building in life cycle, the economic life span for structure as well as the elements of the building should be identified first. Based on the discussion in Chapter 4.3, many of the existing research studies on LCC are based on the international literature (Ouyang et al. 2009; Zhang & Xiao 2009; Ying & Neng 2010; Ouyang et al. 2011). The economic life span of the building components will be calculated according to particular product warranty information and recommendations by the Australian Institute of Cost Planners. The costs for replacement and repair in the operation stage depend on the economic life span of the components.

iv) Sustainability

Sustainability will be assessed based on the life cycle energy consumption that will include embodied, operating energy, and end of life disposal energy use.

The critical area for sustainability in the sustainable residential model is life cycle energy that is measureable for items such as embodied energy, operating energy, construction and demolition waste and the potential carbon sequestration of renewable materials. These sub-criteria allow for a comparison with the traditional residential development model based on heavy materials.

The equation of calculating the life cycle energy for the model is as follows:

$$LCE = CE + EE + REE + DDE \quad (3)$$

Where:
LCE = Life cycle energy
CE = Construction energy
EE = Embodied energy
REE = Recurrent embodied energy
DDE = Demolition and disposal energy

This formula will be applied on a 50-year life cycle. The calculation will all be measured using today's energy values expressed in megajoules. These calculations will also be performed on the sustainable timber redesigned cases to provide a comparison for analysis.

Construction energy is the energy used in the building process for the homes under construction. This includes fuel for excavation, large and small tools for construction and human energy and transport of site workers. Small tools are excluded from the study, as they are insignificant compared to heavy machinery and fuel for plant and equipment. Human energy consumption is also excluded due to inadequate data to calculate the energy intake of particular trades people. Transport of workers is also excluded as information for particular individual workers such as distance from home to work and the types of vehicles used was beyond the scope of this study. The energy for heavy plant and equipment use on site during construction will be measured in the testing of the sustainable model.

Embodied energy is the energy used to produce the construction materials in house building. It includes raw material extraction, fabrication and transport between manufacturing and to site. This will be calculated using the database known as ICE II. Recurrent embodied energy will also be used to test the model. This is the energy found in materials used in the maintenance of the replacement materials.

Demolition and disposal energy is the calculation of plant used to demolish the houses based on fuel consumption (diesel). It will also include the energy used to transport the equipment to and from the building site. Disposal energy will be calculated by measuring the energy used by the trucks travelling from the site to the closest waste facility and the return trip.

7.5 Conclusion

This chapter commenced by discussing the challenge of adopting innovation in the construction sector due to the complex interactions of actors within the industry. The typical procurement process of residential development was also investigated. A sustainable model was proposed that presented a circular material flow and the potential benefits of using timber to replace traditional heavy materials. The potential benefits were identified in the project areas of time, cost, sustainability and timber performance (quality). The current residential development model of residential construction was described from information from 32 homebuilders and then a sustainable timber development model was developed. The potential implications and benefits to clients and developers as a result of adopting a sustainable development model were discussed showing possible improvements to the issues of sustainable development, time and cost. Changing the current misperceptions of timber in construction was also seen as critical to successful adoption of a sustainable residential development model.

The following chapter will seek to test whether the potential benefits of implementing a sustainable timber residential building model can be achieved when applied to real residential case studies based on envelopes built with heavy materials. Current concrete and brick designed homes are the basis of the case studies and these are used to compare a sustainable timber home with the same floor area and thermal resistance. The main performance indicators compared are sustainability, cost, time and thermal performance. Tools used to conduct the comparative case studies include a life cycle energy assessment (sustainability), a life cycle costing (cost), and a construction schedule (time). A thermal modelling program is used to compare thermal properties of the base case with the proposed timber model.

Chapter 8 Case studies and model verification

8.1 Introduction

The aims of this chapter are to verify the sustainable residential development model using timber as an alternative to the heavy materials currently used in residential construction. The verification will include assessing timber performance against performance criteria identified in the sustainable model in Chapter 7.5.3. The results will then be compared to the performance of heavy materials when assessed using the same criteria. The performance criteria are: user comfort (thermal), time of construction, life cycle costing and life cycle energy. Ten case studies of residential projects will be used as the basis for testing the performance criteria and verifying the sustainable residential development model.

This chapter begins by identifying the process of case study selection of the heavy material homes and then analyses the results of the case study projects. Data analysis begins with the thermal performance rating of these homes and compares the cost, time and life cycle energy based on geographic region, ground floor area, and building orientation. These results will provide a platform for a redesigned timber envelope alternative that has equivalent thermal performance. Analysis will be then carried out to ascertain the affect of a thermally equivalent timber design on aspects of cost, life cycle energy and time of construction when compared to the current heavy material design using a concrete and brick envelope. Regression analysis in addition to descriptive statistics will be used to analyse the traditional concrete and brick design and the timber redesign and also to allow for the comparison between the current brick and timber envelope options.

8.2 Case study selection methodology

8.2.1 Selection criteria

Thirty-two projects were obtained from four residential developers and these were put through a screening process to ensure the inclusion of projects with enough information to allow for calculation of materials and for excavation activities, and to enable a redesign in timber. Pertinent information included dimensioned architectural plans, floor plans and elevations, a site plan with contour lines and reduced levels, and structural plans showing the type and specifications for the concrete floor slab. The designs lacking these details were excluded along with those that had a mix of different wall envelope materials (e.g. aerated concrete, fibrous cement or concrete block). This exclusion was to allow for projects with concrete floors and brick veneer to be compared to timber based on a particular design and to keep the scope of the study within manageable limits. Only roof envelopes with concrete tiles were included to keep the envelope structure consistent for the wall and floor redesign using timber. Metal roof projects were excluded, as they require a lighter floor, wall and roof framing system. Table 8.1 summarises details on the materials that are included in the case studies for both the original concrete and brick design and the redesigned timber alternative.

Projects situated on steep sites were also removed from the study as they have been shown to be more energy dependent for heavy materials when compared to timber during the earthworks stage (Forsythe & Ding 2011). Their study also showed that greater energy was required for earthworks in highly reactive soil or rock for heavy materials compared to timber homes. To avoid distorting results in favour of the timber structure in this study, sites with minimal slopes were used and subsoil conditions were M class (moderately reactive clay). The final rejection criterion was the age of the project. Projects constructed prior to the last five years were not included so as to remove the influence of legislation and design changes. Once the selection process was complete there were ten projects remaining for data analysis.

The number of case studies in this study and the associated selection method conforms to the literature on multiple case study designs discussed by Yin (2009) and is classified as literal replication. Literal replication is used to confirm propositions about a particular group of cases by limiting the variables in the cases chosen. Yin (2009) claims that 6-10 case studies allow for a limited number of variable conditions to be tested in the cases and if these cases confirm the initial suggestions then this is compelling evidence that the propositions are correct. The initial propositions of the case studies in this study are that timber construction with the same thermal rating as heavy materials performs better in the time, cost and energy characteristics. The propositions can be described in the following terms.

If timber thermal performance = heavy material thermal performance
Then

4) Timber construction time < heavy material construction time
5) Timber life cycle cost < heavy material life cycle cost
6) Timber life cycle energy < heavy material life cycle energy

These propositions will be verified through an analysis of the case studies based on traditional designs compared to a sustainable timber design. The next section summarises the details of the particular case studies used in the analysis section of this chapter.

8.2.2 The selected projects

The ten case studies are based both in Sydney suburbs and regional areas to the north, south and west of the Sydney metropolitan area. These have different seasonal climates that may affect the heating and cooling requirements of the homes. Both one- and two-storey homes were included as well as different orientations to the sun. A variety of homes based on traditional materials with differing gross floor areas (GFA's) is included. Table 8.1 summarises the information about the projects selected for use in the study.

Table 8.1 provides details of the suburb, solar orientation, number of storeys, and GFA. GFA excludes the garage and stair opening according to the definition provided by the New South Wales Consolidated Regulations.

Table 8.1 Case study information 10 concrete /brick envelope homes

Project No.	Post code	No. of storeys	Gross floor area (excluding garage) m^2	Front of house orientation	Azimuth House entry
1	2145	2	290	North	0°
2	2171	2	334	NNW	345°
3	2321	1	171	East	90°
4	2529	2	281	SSW	160°
5	2321	1	192	East	90°
6	2170	2	246	East	90°
7	2154	2	260	South	180°
8	2321	1	171	North	0°
9	2144	2	240	West	270°
10	2800	2	124	ESE	100°

The construction method of the concrete slab and brick veneer is the same in all ten cases and based on the architectural drawings and structural slab details included in the project documentation provided. Cut and fill requirements and works for retaining walls have been included where designed for particular projects. Table 8.2 provides detail of the materials used in the selected projects.

Table 8.2 Building envelope materials for traditional residential development

Building Component	Brick veneer home
Sub-floor	Sand blinding Concrete piers (in area of fill) 200um Waterproof membrane
Structural floor (Ground Floor)	EPS foam/reinforced concrete ribs Reinforced concrete floor
Floor covering (Ground Floor)	Ceramic tiles
Structural floor (First Floor)	Timber I-beams /Chipboard
Floor covering (First Floor)	Carpet with underlay
Internal wall lining	10mm Plasterboard & paint finish
Wall structure	90mm Pine timber frame Builders wrap/vapour barrier 50mm Air cavity
External cladding	Extruded clay brick
Internal ceiling lining	13mm Plasterboard
Roof structure	Pine timber frame R3.5 to living areas Roof sarking
Roof covering	Concrete tiles

Table 8.2 contains the materials used for the traditional designs used in the case studies. This information is obtained from the project drawings that have been provided by the volume building companies. The materials have been separated into components to allow for a logical comparison with the timber alternative. The following section will detail the process of changing the traditional designs to suit the use of timber in the building envelope.

8.3 Redesigning case study projects for using sustainable timber

A number of factors were considered in the redesign of the concrete and brick case study projects to incorporate a timber optimised alternative. These factors include similar thermal ratings, compliance to Building Codes and Australian Standards and the provision of the same functional areas as the concrete and brick projects. The other consideration was designing the timber buildings for the most commonly used methods and materials used in the construction industry.

The first aim was to achieve a thermal performance equivalent to the traditional material cases to provide a fair comparison for time, life cycle costing (LCC) and life cycle energy (LCE). The thermal performance of the ten brick projects was calculated and a variety of timber envelope options were investigated to obtain the design that performed similarly in thermal performance. The main differences noted between the heavy material structure and timber redesign occurred in the ground works, substructure and wall elements.

i) Ground works

Where excavation was required, fill was distributed to provide a level area for the underfloor such that minimum floor heights under the timber structure were maintained according to the Building Code of Australia (BCA 2013).

ii) Footings

The garage footings were designed for a reinforced waffle pod concrete. This design was based on the original structural drawings and the remaining house structure on concrete pad footings as per the structural designs for areas of cut and fill. These were spaced to allow for the floor bearers to comply with the Australian Standards for timber framing (AS1684.2 2010).

iii) Floor structure

Two timber structural floor systems were designed to achieve thermal ratings of the brick cases depending on the climate of the particular base cases. Both were designed with a proprietary galvanised vertical footing system that complied with Australian Standards and ranged in height from 400mm to 1200mm high; both also consisted of (2 No) 140 x 45mm H3 treated pine bearers (MGP 10) and 90-120mm x 45mm H3 treated pine floor joists (MGP 10). The first flooring option had 19mm hardwood flooring with an air gap of minimum 90mm plus R3.1 insulation enclosed by 12mm plywood fixed to the bottom of the bearers. The second flooring option was 8mm ceramic tiles laid on 15mm compressed fibre cement on top of the joists with no insulation below. Both flooring options have timber cladding to enclose the underfloor area of the home except in Project No. 10, which had the timber, insulated floor but the subfloor was not enclosed.

iv) Wall envelope

The wall element chosen for all ten timber options consisted of interior plasterboard, 140 x 45mm H2 treated pine with R3.1 wool insulation, breathable wall wrap, 38 x 45mm H3 treated pine vertical wall battens, and a cladding of 19mm H3 treated finger jointed pre-primed pine.

A summary of the envelope designs making up the main components of the brick and timber designs are listed in Table 8.3. Table 8.3 provides material systems for both the brick and timber options using standard designs for brick and standard material sizing for the redesigned timber alternative. Material sizing and choice of envelope also considered the most efficient way to achieve equal thermal rating. The process of calculating the thermal performance of the two different designs along with the method of calculating LCC and LCE are discussed in the next section.

Table 8.3 Redesigned timber building envelope design

Building Component	Brick veneer home	Timber clad home
Sub floor	Sand blinding Concrete piers (in area of fill) 200um Waterproof membrane	Waffle pod concrete slab for garage only Concrete piers Galvanised steel piers-braced 19mm timber cladding wall enclosure
Structural floor (Ground Floor)	EPS foam/reinforced concrete ribs Reinforced concrete floor	140mm Treated pine bearers R3.1 Insulation 90-120mm Treated pine joists 12mm Ply under floor covering
Floor covering (Ground Floor)	Carpet with underlay/ceramic tiles	19mm Hardwood flooring OR Ceramic tiles on 15mm fibrous cement sheeting
Structural floor (First Floor)	Timber I-beams Chipboard	Timber I-beams Chipboard
Floor covering (First Floor)	Carpet with underlay	Carpet with underlay
Internal wall lining	10mm Plasterboard	10mm Plasterboard
Wall structure + insulation	90mm Pine timber frame Builders wrap/vapour barrier 50mm Air cavity	145mm Treated pine framing R3.1 Insulation batts Builders wrap/vapour barrier 38mm Air cavity/vertical battens
External cladding	Extruded clay brick	Painted timber cladding Painted timber architraves
Internal ceiling lining	13mm Plasterboard	13mm Plasterboard
Roof structure + insulation	Pine timber frame/truss R3.5 to living areas Roof sarking	MGP 10 Pine Timber frame/truss R3.5 to living areas Roof sarking
Roof covering	Concrete tiles	Concrete tiles

8.4 Assessing variables in the sustainable residential model (SRD)

This section explains the processes for assessing the variables (critical performance criteria) in the sustainable residential development model as discussed in Chapter 7.5.3. The variables are user comfort (thermal performance), construction time, life cycle costing (LCC) and life cycle energy (LCE). The assessment takes a case study approach by using ten completed housing projects built with traditional heavy materials as the baseline for comparison. The redesigned timber cases are assessed and compared to the traditional designs using the same variables to test if the model is more sustainable from a life cycle perspective. The process of this assessment is expounded in the following sections.

8.4.1 Thermal performance modelling of case studies - Traditional versus timber design

Thermal comfort of residential buildings has many influences including airflow, humidity, individual occupant inclinations and activity, and other combinations of factors (Moss 2008). This leads to occupants heating and cooling to suit their particular preferences so it is challenging to predict accurately the energy required for the thermal conditioning of occupied premises. Thermal simulation software is often used to predict heating and cooling loads required for homes of different designs, orientation, climate zone and insulation properties. The case studies in this research use thermal modelling to obtain the thermal performance of each case for both traditional and redesigned timber projects.

AccuRate was the computer simulation program used to compare the projects and work through inputs of material selections, envelope orientation, wall, floor and roof insulation and shading devices in addition to aspects such as window size and thermal specifications. The output of the analysis is a star rating based on the particular climate area and an estimated annual heating and cooling energy requirement. The higher the star rating, the more efficient the building is for thermal conditioning and the lower the energy expenditure. AccuRate is one of the software programs accepted as part of the Nationwide House Energy Rating Scheme approved by the Building Code of Australia (BCA). Refer to Chapter 4.6 for details on thermal modelling and performance.

The brick veneer projects used in this study conform to Australian Building Codes for thermal performance although they were analysed through the modelling program AccuRate to model heating and cooling loads. Table 8.4

provides the star rating for each of the ten projects in addition to the heating and cooling loads.

Table 8.4 Thermal star rating for the ten brick veneer projects

Project ID	Thermal Star Rating (Stars)	MJ/m² /yr.			GFA (m²)	Azimuth House entry
		Cooling	Heating	Total heating & cooling		
1	5.9	49.4	40.2	89.6	290	0°
2	5.8	28.4	24.8	53.2	334	345°
3	5.4	58.9	40.8	99.7	171	90°
4	4.9	30.2	75.1	105.3	281	160°
5	5.6	52.7	44.0	96.7	192	90°
6	5.2	63.5	46.1	109.6	246	90°
7	6.1	25.0	24.5	49.5	260	180°
8	4.7	66.3	58.0	121.3	171	0°
9	6.2	31.0	17.6	48.6	240	270°
10	4.9	7.6	288.5	296.1	124	100°

The results in Table 8.4 show generally that areas with hotter annual temperatures required greater cooling than heating (Projects 1, 3, 5, 6, 8 and 9, all in a regional area north of Sydney) and homes in areas with mild temperatures within the suburbs of Sydney had heating needs similar to cooling (Projects 2 and 7). The exceptions were the houses in Sydney orientated to the west that required greater cooling energy (Projects 4 and 10). Orientation also affected heating and cooling loads of two homes that were identical and found north of Sydney (Project 3 and 8). The house orientated to the north (Project 8) had poorer thermal performance than the same design facing east (Project 3). The home requiring most annual energy made up almost entirely of heating was found in Project 10 that is based in a regional area west of Sydney that has a low average annual temperature and sub zero winter temperatures.

The second stage of thermal analysis involved analysing the thermal performance of the redesigned timber cases. This provides a comparison to the brick veneer cases with the same GFA. Based on the thermal star rating results of the brick veneer projects, timber homes were designed to match the thermal performance through increasing wall and floor dimensions. The changes include the structural components of the sub-floor and floor, external wall and lining, and roof. The timber design was in accordance with the timber framing code of Australia. Sizing of the wall envelope, floor envelope and cladding were selected to incorporate common standard timber sizes and thermal performance. The floor structure included the use of timbers that were both insect and moisture resistant and could take the load of the wall envelope. This was required to allow for the additional weight of timbers in the wall due to increased envelope width. The wall structure was designed to resist insect and moisture attack and to increased insulation. The increased width of wall frames had flow on effects for door jambs and window reveals that increased the cost and material volume. Using timber cladding introduced an element that required painting and ongoing expense in maintenance requirements. Table 8.5 presents the star rating and heating/cooling load comparison between the brick veneer projects and the redesigned timber projects.

Table 8.5 Comparison of thermal conditioning - Brick versus timber

Project No.	Thermal Star Rating (Stars)		Heating & cooling ($MJ/m^2/year$)		GFA (m^2)	Azimuth House entry
	Brick	Timber	Brick	Timber		
1	5.9	5.6	89.6	95.5	290	0°
2	5.8	6.0	53.2	44.2	334	345°
3	5.4	5.0	99.7	115.1	171	90°
4	4.9	5.8	105.3	86.5	281	160°
5	5.6	5.5	96.7	98.1	192	90°
6	5.2	5.4	109.6	102.1	246	90°
7	6.1	6.1	49.5	50.3	260	180°
8	4.7	4.2	121.3	137.7	171	0°
9	6.2	6.1	48.6	49.4	240	270°
10	4.9	5.4	296.1	252.9	124	100°

Table 8.5 displays the AccuRate thermal star rating for the ten brick veneer projects with the optimised timber design that obtains the AccuRate star rating closest to the brick veneer projects. Eight timber design projects have an enclosed subfloor area and tiles on fibre cement flooring (TFC). Project 4 has an enclosed subfloor area with the insulated floor system. Project 10 only has the insulated floor system. All ten timber redesign projects have the same wall system as described in Table 8.3. The projects highlighted in yellow in Table 8.5 were the most efficient in thermal conditioning energy requirements. These were all two storey homes and each had the front doors facing differing

azimuths. The thing that may have contributed significantly to their predicted low thermal performance is the shading over windows and walls. Each house had a number of wing walls, awnings and first floor balconies that provided shading for different parts of the home during the day.

The thermal comparison shows that only Project 7 has the same thermal rating and the remaining timber homes are up to 0.5 star points above or below the brick base case projects. In order to examine the effect of these subtle differences a 50-year thermal load calculation analysis was carried out to determine the possible impact on life cycle energy comparisons between the brick and timber homes. This was calculated by first determining the value of 0.1 star rating in energy (Mj/m^2). This was then multiplied by the number of 0.1 stars difference between the brick and timber redesigned home. This was then multiplied by the GFA of the particular project and then multiplied by the life of the home (50 years).

The adjusted thermal analysis results did not alter the life cycle energy of the timber homes significantly and was therefore not used in the remaining analysis. The adjusted energy analysis is found in Appendix 8.1

8.4.2 Life cycle energy modelling of case studies - Traditional versus timber design

Life cycle energy (LCE) was calculated based on the details as discussed in Chapter 7.5.3. LCE includes cumulative energy demand for ground works, embodied in the materials, heating and cooling, maintenance, demolition and transportation to waste and resource recycling centres. Lighting, cooking and appliance energy is excluded from the study as it is assumed to be equal for both types of construction. Also excluded is the energy required for transportation of labour to the construction site and energy embodied in the manufacturing of small construction tools.

Sub-criteria such as reuse of materials and measurement of renewable materials have been omitted from the sustainable model due to the lack of available data on the rates of reuse of timber for residential development and specific carbon accounting data related to recycling and land fill of individual materials. The reason for excluding operating costs is that designs in the case study comparison have similar thermal performance so energy use for heating, cooling, appliances and lighting are assumed to be the same. This will affect the percentages of the phases of the projects overall life cycle energy. The measurement of life cycle energy for the case studies will be based on embodied energy for materials used in construction, energy used in the major plant and equipment during construction, embodied energy in maintenance materials and end of life activities (demolition and transport of materials to waste resource and recycling centres).

Table 8.6 gives the comparison between brick cases and the redesigned timber cases. Life cycle energy for the 50 years is calculated using the formula from Chapter 7.5.3. The table shows that for each case the timber design option has a lower LCE than for the traditional heavy material design over the 50-year life span.

Table 8.6 Comparison of life cycle energy - Brick versus timber

Project No.	GFA (m^2)	Thermal Star Rating (Stars)		LCE (50 years) (MJ)		LCE (50 years) (MJ/m^2)	
		Brick	Timber	Brick	Timber	Brick	Timber
1	290	5.9	5.6	2,230,507	2,009,116	7,691	6,928
2	334	5.8	6.0	3,051,217	2,827,444	9,135	8,465
3	171	5.4	5.0	1,900,948	1,708,336	11,117	9,990
4	281	4.9	6.2	2,471,915	2,234,080	8,797	7,950
5	192	5.6	5.5	1,947,019	1,760,811	10,141	9,171
6	246	5.2	5.4	2,475,470	2,221,483	10,063	9,030
7	260	6.1	6.1	2,476,941	2,274,446	9,527	8,748
8	171	4.7	4.2	1,851,943	1,696,303	10,830	9,920
9	240	6.2	6.1	2,122,896	1,943,651	8,845	8,099
10	124	4.9	5.4	1,144,086	1,037,806	9,226	8,369

8.4.3 Life cycle costing modelling of case studies - Traditional versus timber redesigned buildings

Life cycle costs (LCC) have been analysed for both the heavy material and timber projects through the phases of the life cycle of 50 years including initial construction costs, maintenance and end of life disposal. Owner and operating costs were excluded in the calculation, as these will be the same for both types of construction. Costs for maintenance and demolition are based on industry rates and are calculated for both base cases and timber redesign scenarios and discounted at a rate of 5% to allow for the future costs to be presented in today's value to allow for comparison. This is necessary as the maintenance occurs intermittently over 50 years and demolition is assumed to take place in 50 years according to the total life cycle time. Table 8.7 contains the items that are required for maintenance and the associated life span.

Table 8.7 Replacement times for maintenance/demolition items

Maintenance Items	Inclusions	Life span (Years)	Brick	Timber
Internal painting	Paint and labour	10	✓	✓
External painting	Paint and labour	7	X	✓
Bathroom/laundry tiles	Demolition/disposal, waterproof, FC wall sheets, tiling, fixtures	25	✓	✓
Garage door	Disposal/Supply and install	25	✓	✓
Windows (internal architraves	Disposal/Supply and install/ paint windows & architraves	25	✓	✓
Ceramic tiles	Disposal/Underlay/ carpet, installation	25	✓	✓
External doors	Disposal/Supply and install/ hardware/ paint	25	✓	✓
External door frames and architraves	Supply, install and paint	25	X	✓
Timber cladding	Disposal/Supply and install and paint	25	X	✓
Demolition	Entire house + footings	50	✓	✓
Disposal	Entire house + footings	50	✓	✓

Source: Australian Management Manual 2002; Individual product warranty

Table 8.7 shows the life span for material replacement and maintenance for the brick house and the timber redesign. To allow for all costs, the 50-year formula established in Chapter 7.5.3 has been used as the basis for LCC in the selected projects.

Exclusions from the LCC include the interior fit out and services and operating costs. The reason for their exclusion is that they are common to both types of construction. Other costs associated with construction of residential premises such as land purchase, design consultants, legal services and approvals have also been excluded from the calculations. Building LCC include the excavation, retaining walls, house construction, recurring costs and end of life disposal.

An operating energy comparison was conducted using Project 2 to allow for the cost impact of slightly different thermal load requirements between the brick veneer case and timber redesigned home. The reason for calculating the impact of this cost difference was to check if the thermal star rating difference between the projects would impact on LCC.

The method for working out the cost difference was to calculate operating energy cost for a year and then convert this into 50 years using net present value calculations with a discount rate of 5%. Project 2 had a difference of 0.2 thermal star points between the brick and timber design. The method used to calculate the impact of 0.2 stars was first to establish the average break up of energy use for NSW households. This was obtained from a NSW government energy break up report for families and an IPART report of the average 5-person household energy usage (IPART 2012; NSW Government 2013). The heating and energy load information from Project 2 thermal modelling was used in conjunction with data from reports to calculate the total operational costs for the brick and timber cases. Over a 50-year life cycle period the point 0.2 star differences represented a cost difference of 0.0015% in net present value or .00075% per 0.1 AccuRate star rating (see Appendix 8.2). Due to the insignificant cost impact on the overall cost comparison, no adjustments were made to the final LCC comparison between the brick and timber projects. Table 8.8 provides the total LCC cost of the ten cases.

Table 8.8 Comparison of life cycle costs - Brick versus timber

Project No.	GFA (m^2)	Thermal Star Rating (Stars)		LCC (50 years) ($)		LCC (50 years) ($/$m^2$)	
		Brick	Timber	Brick	Timber	Brick	Timber
1	290	5.9	5.6	179,366	179,464	618	619
2	334	5.8	6.0	229,612	225,657	688	676
3	171	5.4	5.0	215,684	190,336	1,261	1,113
4	281	4.9	6.2	186,158	170,822	662	608
5	192	5.6	5.5	193,320	196,297	1,007	1,022
6	246	5.2	5.4	178,372	164,434	725	668
7	260	6.1	6.1	184,072	178,514	708	687
8	171	4.7	4.2	176,638	187,807	1,033	1,098
9	240	6.2	6.1	148,430	160,556	619	669
10	124	4.9	5.4	123,881	118,873	999	959

Table 8.8 summarises the total LCC for the brick veneer design compared to the timber-redesigned projects. This will be separated into the different life cycle stages in the detailed analysis of the case studies. Projects 5, 8 and 9 are more expensive in the timber design and the remaining projects are more expensive for the brick veneer design. Refer to the detailed analysis on LCC in the discussion of results section of this chapter. The next section introduces the process of calculating the time variable in the sustainable residential development model.

8.4.4 Construction time modelling - Traditional versus timber redesigned buildings

Time considerations are critical to construction projects as discussed initially in Chapter 4.4. This is due to costs to both builders and clients associated with time delays beyond planned or expected project finish dates. Builders need to allow for ongoing costs associated with establishing and operating the site with items such as the supply of temporary fencing and worker facilities in addition to power and water costs. Delay in building works slows progress payments that can affect a builder’s cash flow, profits and overheads. The client is also affected by construction speed, as their return on investment will reduce over time if the project is not completed to the schedule. Losses occur through lost opportunities on money invested and/or ongoing interest on borrowed finances.

A schedule estimate has been prepared for both the brick base cases and the timber redesign using an optimum scheduling method. This involves using industry professionals and industry association guidelines/trade averages applied to both the base case and the redesign. This scheduling allows for the most efficient overlap between trades and the optimum outcome. This research acknowledges that real life projects experience delay in trade coordination due to supply or lack of supply of trades and other factors such as material availability. However, due to the ambiguity and lack of data for these time delays, they have been omitted from this study.

The scheduling of activities accounts for dependencies that occur between trades according to current practice although innovative practices new to the building industry are not used in the calculations (e.g. prefabricated bathroom modules, completed wall or floor panels). The information used for the scheduling (building program) has been obtained from industry associations, experienced building professionals, builders, carpenters and other trades people with over 20 years' individual experience in residential building. Table 8.9 provides the sources of information for some of the main structural elements of the building envelope investigated and the size of teams used for calculating the time of completing each element.

Table 8.9 Scheduling information sources and trade team numbers

Building element	Trade	Number of workers	Information sources
Concrete slab footing	Concreters	4	Work Safe Victoria
Pier holes	Excavator	1	Industry professionals
	Labourer/builder	1	Industry professionals
Piers	Carpenter/labourer	4	Builder/carpenter
Timber substructure	Carpenter	3	Builder/carpenter
	Labourer/apprentice	1	Builder/carpenter
Wall frames	Carpenter	3	Builder/carpenter/Westruss Co.
	Labourer/apprentice	1	Builder/carpenter
Roof framing	Carpenter	3	Builder/carpenter
	Labourer/apprentice	1	Builder/carpenter
Brick work	Bricklayers	3	National Federation of

			Bricklayers and Masonry Employees
	Labourer/apprentice	1	Builder/bricklayer
Wall cladding	Carpenter	3	Builder/carpenter
	Labourer/apprentice	1	Builder/carpenter
Roof tiling	Roof tilers	3	Builders/roof tiler
	Labourer/apprentice	1	Builders/roof tiler

Table 8.9 displays the information sources used to establish times for the scheduling used in the case study time modelling comparison between brick and timber. The scheduled work was measured in 8 hour working days however the final results recorded the calendar days from day 1 (Monday-site set up) until the completion of internal painting. An external validity check was conducted by engaging a carpenter with over 20 years' experience in residential construction to produce an independent schedule for each construction process without having access to the results of this research. The carpenter was provided with a set of plans along with the information in Table 8.10 regarding the size of trade teams in order to produce a realistic schedule based on current construction practice. This provided a benchmark tool to check the resulting schedules produced for this research. There were no significant differences between the carpenters estimate for time and those found in the result in the thesis. The carpenter did however emphasise that the schedule was based on no issues occurring with the coordination of trades, material supply and weather. This is known as 'blue sky programming' and is not the usual occurrence. This optimum programming was applied equally to both the timber and brick cases.

Table 8.10 Construction time comparison between brick and timber

Project No.	GFA (m^2)	Construction time (Calendar days)		Difference (%)
		Brick	Timber	
1	290	82	69	-18.8
2	334	74	57	-29.8
3	171	69	58	-19.0
4	281	88	67	-31.3
5	192	59	51	-15.7
6	246	84	69	-21.7
7	260	78	70	-11.4
8	171	71	54	-31.5
9	240	73	65	-12.3
10	124	58	50	-16.0

The initial results showed that the brick veneer projects took an average of 73.6 days compared to 61 days for the timber homes that is a mean of 13 calendar days longer for the brick projects. The difference between the timber and brick ranged from 8 days up to 21 days and this translates between 6 and 15 working days. There was a big difference between the construction time for projects 2, 4 and 8 that may be explained by the design of the floor slabs and wall envelope plan. These three homes had large concrete ground slabs with large drop edge beams and reinforcing requirements. They also had large volumes of brickwork that included columns and other time consuming bricklaying. MS Project was the program used to calculate construction time and this program is a commonly used scheduling tool for the Australian construction industry.

8.5 Data analysis and discussion

This section analyses and presents results from analysing the results of the sustainable residential building model and is broken up into thermal performance, LCE, LCC and time. The performance of the traditional heavy material is presented in each section followed by a comparison with the sustainable timber alternative.

8.5.1 Thermal performance analysis of case study projects

The first thermal results displayed in Figure 8.1 show the energy use for heating and cooling per square metre every year for each project.

Figure 8.1 Thermal performance of traditional materials versus timber (MJ/m²/year)

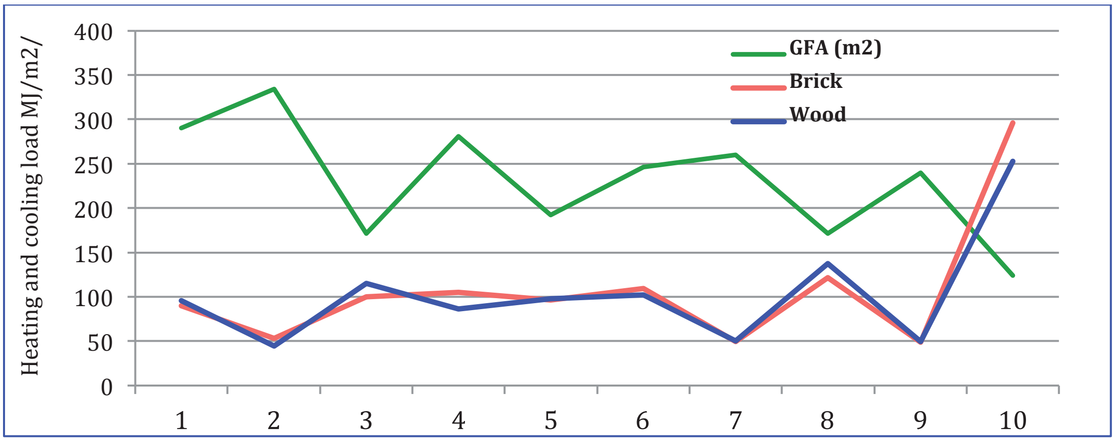


Figure 8.1 shows the energy required to provide heating and cooling for the ten projects comparing the timber and brick homes. The thermal performance is almost the same in every case. It also shows a reducing thermal load as the projects begin to increase in GFA. This may be caused by lower roof spaces areas for two storey homes or greater thermal efficiency in the downstairs living areas due to thermal insulation from the first floor structure. Figure 8.2 compares the thermal performance between traditional material and timber projects using the thermal modelling rating.

Figure 8.2 Comparison between thermal star rating - Timber versus brick

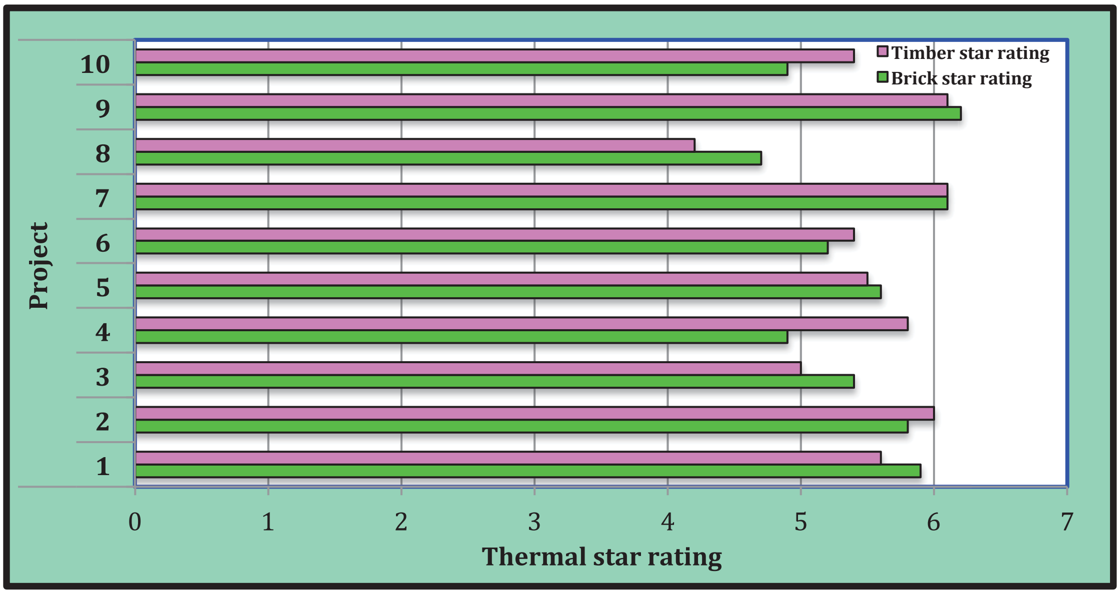


Figure 8.2 shows that for most projects there is only a slight difference between the timber and brick thermal star rating performance. This demonstrates that it is possible to achieve similar thermal performance for timber compared to traditional heavy materials and provide the same thermal comfort. Therefore the perception provided in the questionnaire and survey responses that timber is inferior in thermal performance to heavy materials is incorrect. The capacity of timber being able to achieve equivalent thermal performance also means that time, cost, and carbon impact can be compared on homes with similar thermal star ratings. Those projects with a difference in thermal ratings are dealt with by

adjusting the life cycle energy to account for the slight difference in heating and cooling for the 50-year life cycle. This is discussed in the next sub-section.

8.5.2 LCE performance analysis of case study projects

Building life cycle energy has been calculated for the ten projects and includes the embodied energy in the materials, energy used in excavation through the use of heavy plant and equipment, energy in replacement materials for the home over 50-year life service, in addition to the end of life disposal. Table 8.6 above presents the cumulative energy demand for the brick and timber projects over a life cycle of 50 years. Table 8.11 presents the further breakdown of the life cycle energy by stages for both brick and timber projects.

Table 8.11 Summary of life cycle energy by stages per m^2 GFA

Project No	Life Cycle Energy (MJ/m^2 GFA)							
	Construction		Maintenance (50 yrs life span)		End of life		Total Life Cycle Energy	
	Brick	Timber	Brick	Timber	Brick	Timber	Brick	Timber
1	4,533	3,693	3,047	3,164	111	70	7,691	6,928
2	5,213	4,532	3,810	3,857	112	76	9,135	8,465
3	6,743	5,627	4,114	4,212	260	151	11,117	9,990
4	5,075	4,278	3,609	3,601	113	71	8,797	7,950
5	6,067	5,062	3,831	3,954	242	155	10,140	9,171
6	5,804	4,794	4,140	4,163	119	74	10,063	9,030
7	5,457	4,629	3,954	4,044	117	75	9,527	8,748
8	6,375	5,517	4,180	4,229	275	174	10,830	9,920
9	5,033	4,171	3,716	3,866	97	61	8,845	8,099
10	5,584	4,868	3,458	3,379	184	122	9,226	8,369
Mean	**5,589**	**4,717**	**3,822**	**3,847**	**161**	**103**	**9,572**	**8,667**
Standard Deviation	**672**	**596**	**351**	**361**	**70**	**43**	**1,027**	**925**

Table 8.11 breaks down the life cycle energy into phases and shows the energy per m^2 of GFA. The average energy per square metre of floor area for the construction phase was 5,589MJ/m^2 for brick and 4,717MJ/m^2 for timber, which is about 18% less than brick. Maintenance energy per m^2 for timber was marginally more than brick with averages of 3,847MJ/m^2 and 3,822MJ/m^2 respectively.

The mean of end of life energy was much higher for brick (161MJ/m^2) than timber (103MJ/m^2). Total life cycle energy per m^2 GFA averaged 9,572MJ/m^2 for brick and 8,667MJ/m^2 for timber, approximately 10% more on a life cycle perspective. The standard deviation around the mean was 1,027MJ/m^2 and 925MJ/m^2 indicating a higher dispersion for brick projects. This could be related to the wide variety of impacts for brick project energy due to site slope and conditions dictating retaining structures.

Table 8.12 Summary of life cycle energy by stages in percentage

Project No	Life Cycle Energy (%)					
	Construction		Maintenance (50 years life span)		End of life	
	Brick	Timber	Brick	Timber	Brick	Timber
1	58.9	53.3	39.6	45.7	1.5	1.0
2	57.1	53.5	41.7	45.6	1.2	0.9
3	60.7	56.3	37.0	42.1	2.3	1.5
4	57.7	53.8	41.0	45.3	1.3	0.9
5	59.8	55.2	37.8	43.1	2.4	1.7
6	57.7	53.1	41.1	46.1	1.2	0.8
7	57.3	52.9	41.5	46.2	1.2	0.9
8	58.9	55.6	38.6	42.6	2.5	1.8
9	56.9	51.5	42.0	47.7	1.1	0.8
10	60.5	58.2	37.5	40.4	2.0	1.5
Mean	**58.5**	**54.4**	**39.8**	**44.5**	**1.7**	**1.2**

Table 8.12 shows that the percentage of energy use at the construction stage to the total life cycle energy ranged from 57-61% with an average of 58.5%. Maintenance energy ranged between 37% and 42% at an average of 39.8%. End of life energy was nominal and composed only 1.7% of the total life cycle energy. This energy embodied in heavy materials presents a significant opportunity for reduction in a homes' embodied energy through the use of alternate materials.

The mean energy use for timber life cycle phases was 54.4% for construction, 44.5% for maintenance and just 1.16% for end of life. End of life energy for the brick projects averaged 44% higher than the timber end of life (1.7%) although this has minimal impact on the whole life cycle energy.

Figure 8.3 shows the comparison between timber and brick projects of the mean energy break up through the phases of life cycle energy.

Figure 8.3 Brick versus timber mean life cycle energy results by individual phase

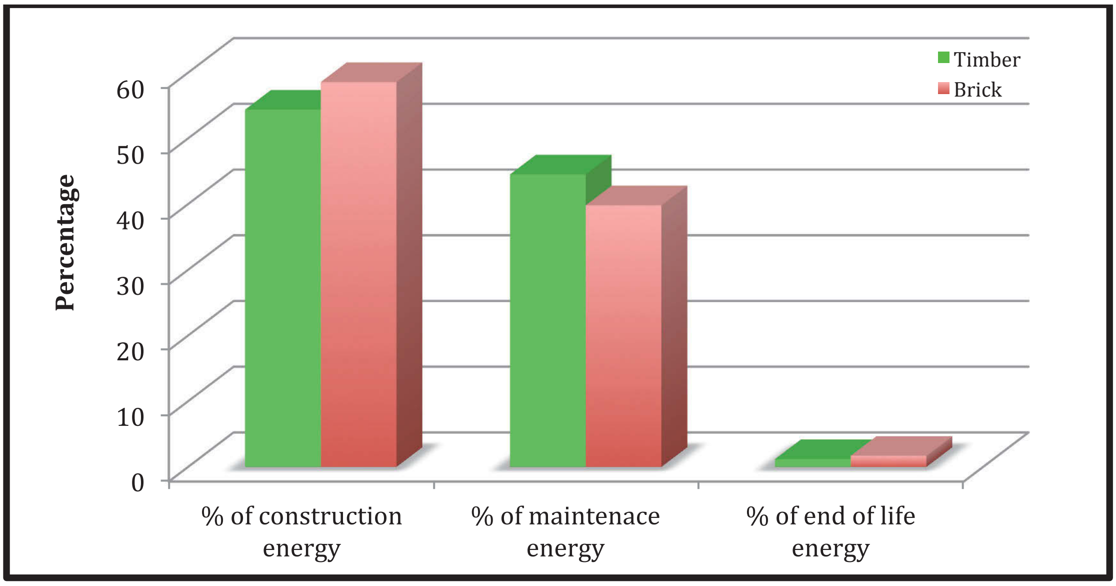


Figure 8.3 shows the energy breakdown phases (using percentage) for the brick and timber LCE. The energy for brick construction was more than for timber in the construction phase however usually less for the maintenance phase. The energy for end of life phase of the case studies was only between 1-2% with only 0.5% difference between timber and brick with brick requiring more energy for this phase. Life cycle energy per metre squared of GFA was compared between the ten brick projects and showed only minor differences. This was the same for the timber cases. The three highest LCE per metre squared were single-storey homes. This may be related to the high volume of concrete in the floor slabs per overall GFA and the large roof areas.

Figure 8.4 Life cycle energy per metre square. Timber versus heavy materials

Figure 8.4 shows the comparison between brick and timber. Timber is consistently lower in life cycle energy than brick in all ten cases. The breakdown of life cycle energy into construction materials, maintenance and end of life has been charted in Figure 8.5 to demonstrate the difference between each project over the 50-year life of the projects. It also compares the LCE between brick and timber.

Figure 8.5 Timber and brick life cycle energy results-by phases

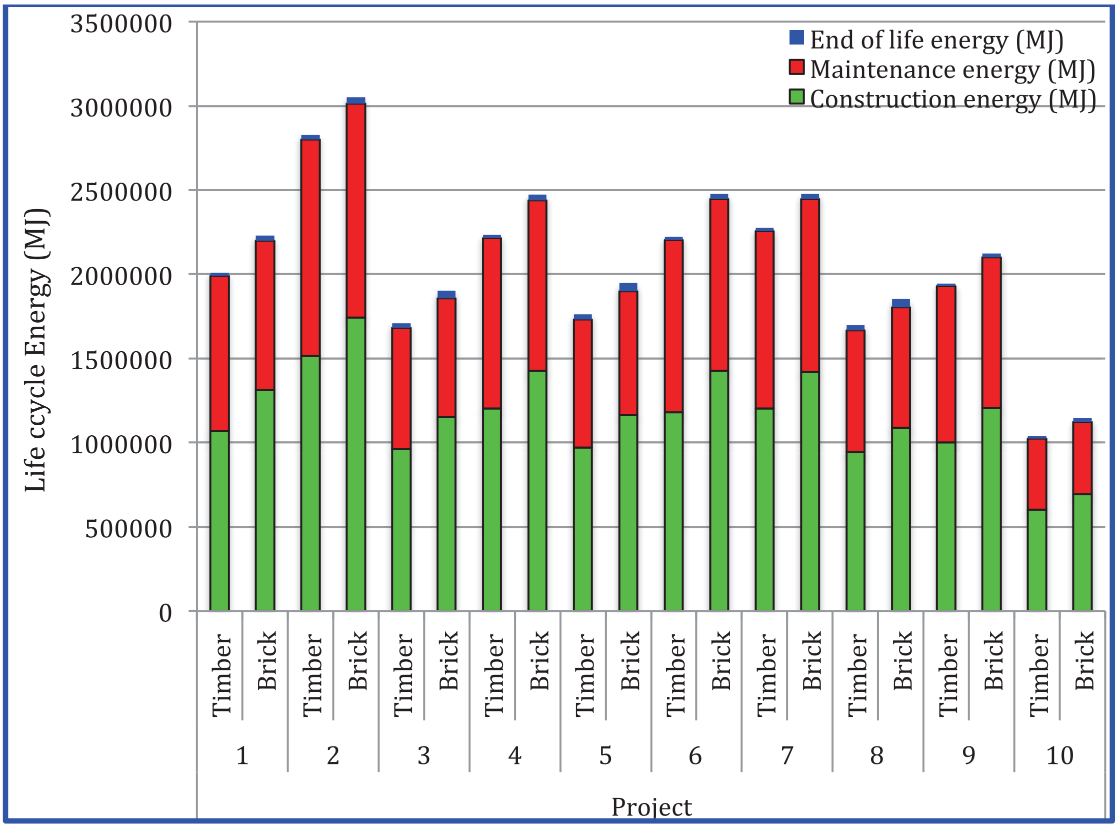
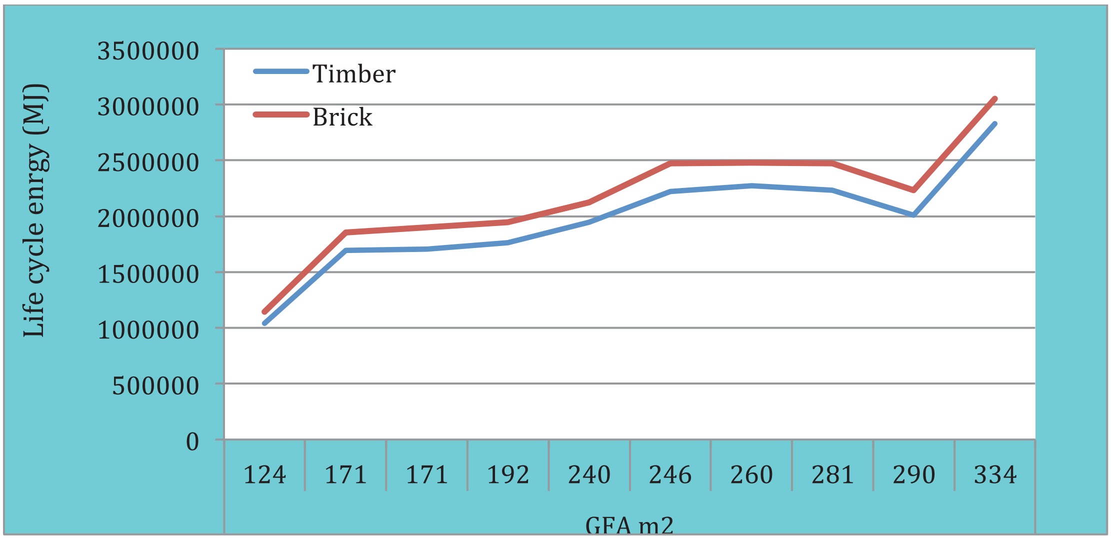


Figure 8.5 shows that timber projects have a similar distribution of energy consumption in the construction and maintenance phases with a small portion of energy in the end of life phase.

Earlier in this chapter a general trend was established between total life cycle energy of brick projects and GFA and Figure 8.6 provides the correlation between LCE and GFA for both brick and timber designs.

Figure 8.6 Timber and brick life cycle energy and gross floor area



Results for timber correlation with GFA in Figure 8.6 show the same upward trend as with the brick projects demonstrating an increase in energy use as the ground floor area increases. This is most likely due to the increase in materials both in the construction and maintenance phase.

The next analysis in Figures 8.7 and Figure 8.8 focuses on the breakdown of energy in the different building elements.

Figure 8.7 Distribution of LCE across building elements (excluding end of life energy)

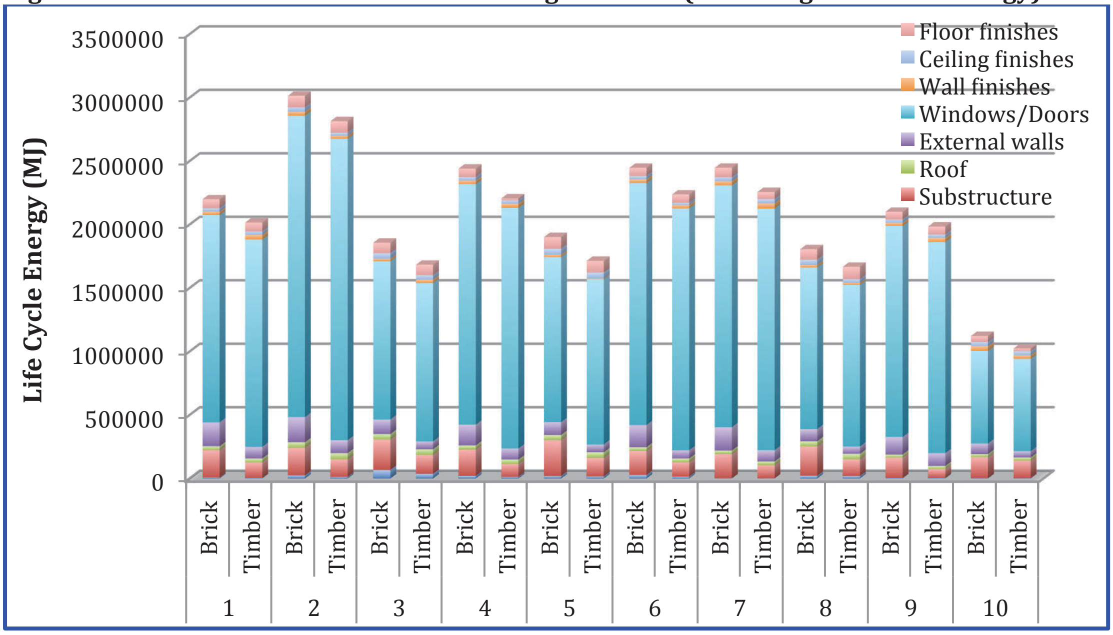


Figure 8.7 shows the comparison between timber and brick LCE. However, the energy embodied in windows/doors make up a large proportion of life cycle energy as they have a replacement life of 25 years and so are included twice in the energy count. Figure 8.8 shows the same LCE elemental breakdown without windows and doors to allow for better analysis of other components as windows and doors are the same for both designs.

Figure 8.8 Distribution of LCE in building elements (excl. windows & end of life energy)

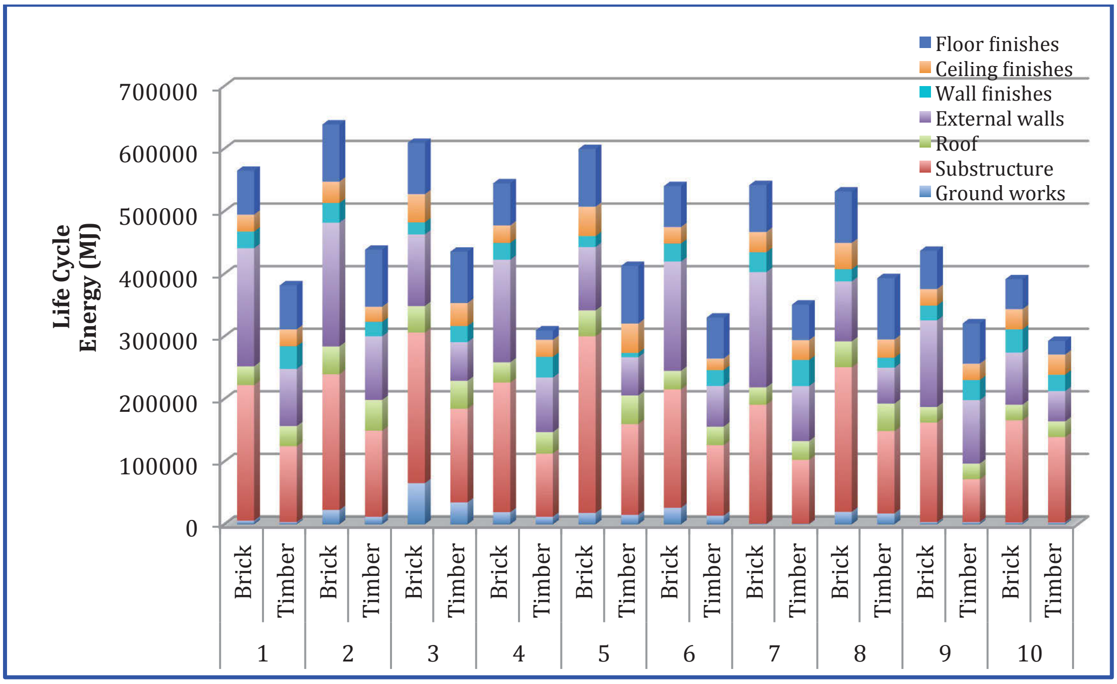


Figure 8.8 reveals the main area of difference between timber and brick LCE by elements (excluding windows and doors). It shows that ground works for brick are higher in most cases although this has relatively little impact on the total results. The most influential elements in LCE are substructure and external walls most likely due to the impact of concrete and bricks in the heavy material projects and despite the replacement of timber cladding in the timber projects. Wall finishes are slightly higher for timber due to external painting that is not required for brick veneer homes. Floor finishes are similar with the exception of where timber flooring is used instead of tiling.

Figure 8.9 Life cycle energy results-Comparison between timber and brick

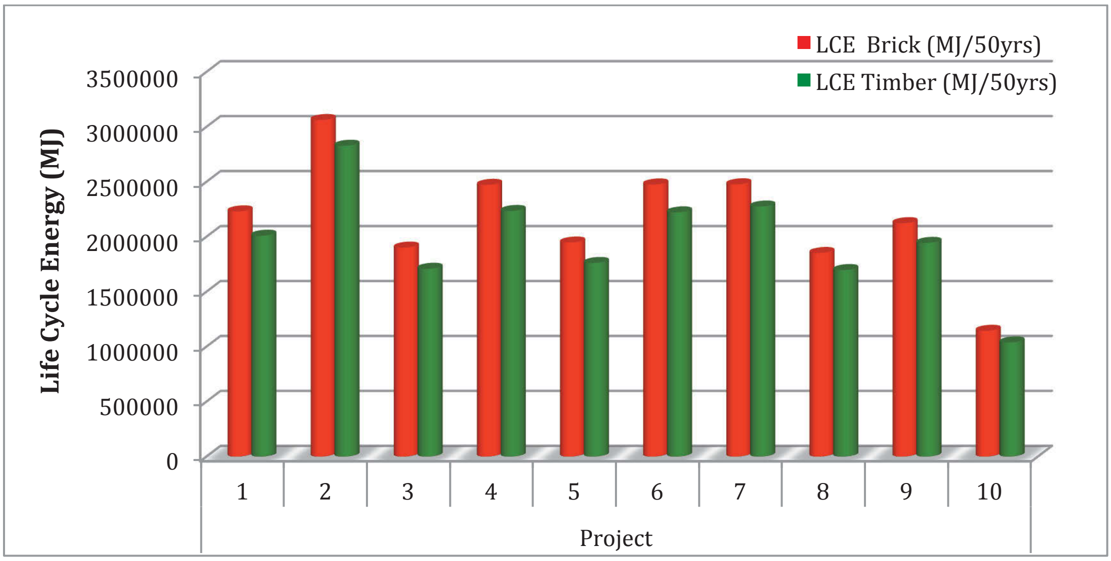


Figure 8.9 shows the combined life cycle energy for the construction, maintenance and end of life of timber and brick homes. Results show that timber homes have lower energy requirements than brick in every case study project. The percentage difference between timber and heavy materials ranges from 8.3% to 11.3% with a mean of 10% less life cycle energy required by the timber homes when compared with concrete and brick homes.

This concludes the data analysis of the life cycle energy comparison between the ten brick and timber projects. A summary of this analysis concludes that timber requires lower energy requirements (10-12.6%) than brick for the 50 years of service when based on equivalent thermal performance. The substructure and external wall elements have the greatest influence on the difference in embodied energy between brick and timber projects (in favour of timber). It is noted that percentage comparisons exclude the use phase in calculations. The following section reviews the comparative case study data for life cycle cost.

8.5.3 LCC performance analysis of case study projects

Life cycle costs were calculated for the heavy materials first and then a timber redesign LCC was conducted for comparison. This section analyses the results for the brick veneer projects first and then compares the timber projects. LCC includes construction, maintenance, and end of life expenses.

Figure 8.10 Brick life cycle costs versus GFA

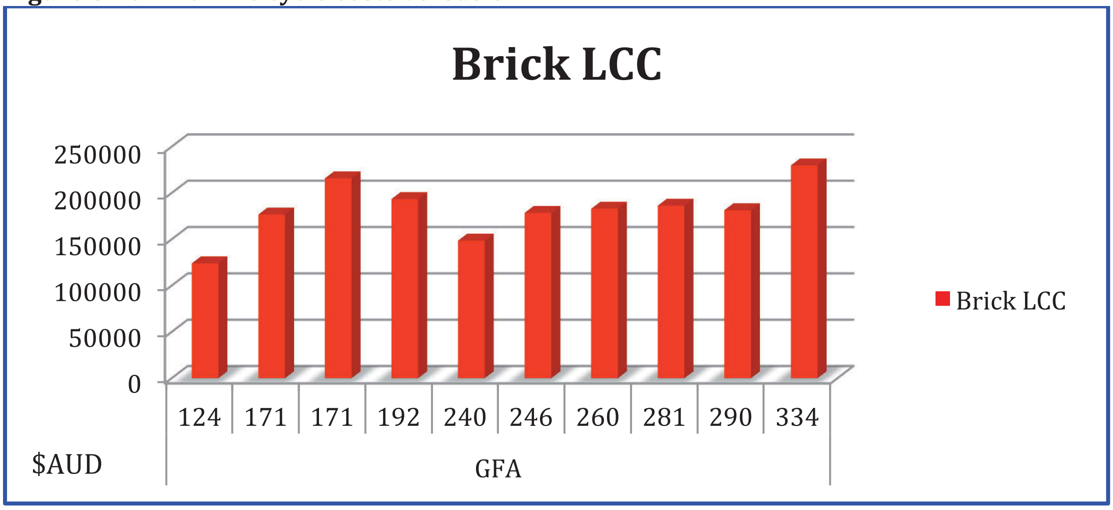


Table 8.10 compares the GFA of the ten brick projects to the LCC and shows there is an increase in LCC with increasing GFA in most cases. The single-storey projects (those with 171m2 and 192m2) appear more expensive and this may be due to high roofing structure cost due to the large roof area to GFA ratio compared to two-storey homes that have a smaller roof to GFA ratio. Table 8.13 presents the building envelope construction costs and life cycle costs per m^2 (GFA).

Table 8.13 Summary of Total life cycle excl. use costing by stages per m² GFA

Project No	Life Cycle Costing ($/m² GFA)							
	Construction		Maintenance (50 years life span)		End of life		Total Life Cycle	
	Brick	Timber	Brick	Timber	Brick	Timber	Brick	Timber
1	542	514	70	100	6	5	618	619
2	602	566	80	104	6	5	688	676
3	1129	960	121	145	11	9	1261	1113
4	582	515	75	89	5	4	662	608
5	884	872	112	142	11	9	1007	1022
6	631	550	88	114	6	5	725	668
7	612	565	90	117	6	5	708	687
8	901	938	120	151	12	8	1033	1098
9	535	553	78	112	6	4	619	669
10	851	804	137	147	11	8	999	959
Mean	**727**	**684**	**97**	**122**	**8**	**6**	**832**	**812**
Standard Deviation	**200**	**186**	**23**	**22**	**3**	**2**	**223**	**209**

The comparison between brick and timber cost per m² GFA in Table 8.13 reveals construction and end of life averages for brick are greater than timber by about 6% and 33% respectively. Maintenance cost of timber is the phase that was about 33% more expensive than brick on average per m². The total mean for brick was $832/m² compared to $812/m² for timber (3% less).

Standard deviation around the mean was $223 and $209 per m² GFA respectively for brick and timber. Both dispersions are quite large although this may be a result of the ground works variation between projects or that projects are located in both city and regional areas. The other influencing factor on the large dispersion around the mean could be the impact of one-storey homes on cost per m². One-storey homes have larger costs per m² GFA, most likely related to significant structural floor costs and large areas of roofing compared to two-storey properties.

Table 8.14 Summary of life cycle costing by stages in percentage

Project No	Life Cycle Costing (%)					
	Construction		Maintenance (50 years life span)		End of life	
	Brick	Timber	Brick	Timber	Brick	Timber
1	87.7	83.0	11.4	16.2	1.0	0.8
2	87.5	83.8	11.6	15.4	0.9	0.8
3	89.5	86.2	9.6	13.0	0.9	0.8
4	87.9	84.7	11.4	14.7	0.7	0.6
5	87.8	85.3	11.1	13.9	1.1	0.8
6	87.0	82.2	12.2	17.0	0.8	0.7
7	86.4	82.3	12.7	17.0	0.9	0.7
8	87.2	85.4	11.7	13.8	1.1	0.8
9	86.5	82.7	12.6	16.7	0.9	0.6
10	85.2	83.9	13.7	15.3	1.1	0.8
Mean	**87.3**	**84.0**	**11.8**	**15.3**	**1.0**	**0.7**

As shown in Table 8.14 the initial construction cost for brick makes up the majority of the life cycle cost with 87% whereas the maintenance costs are significantly lower at 12% and end of life costs just 1%. The results for timber vary slightly from brick in that construction costs are a little lower (84%). The maintenance costs for timber is higher than brick at 15%. The reason for the higher maintenance costs can be attributed to the replacement of timber cladding and the painting of cladding throughout the 50- year life cycle. Timber end of life costs only make up a small percentage of LCC at just 0.7%. It is noted that percentage comparisons exclude the operating energy phase.

The life cycle costing was also analysed by major building elements for both designs. The breakdown of costs into elements will now be reviewed and presented in Figures 8.11 for brick and timber design to better understand how the majority of costs are distributed.

Figure 8.11 Distribution of costs across building elements for brick and timber buildings

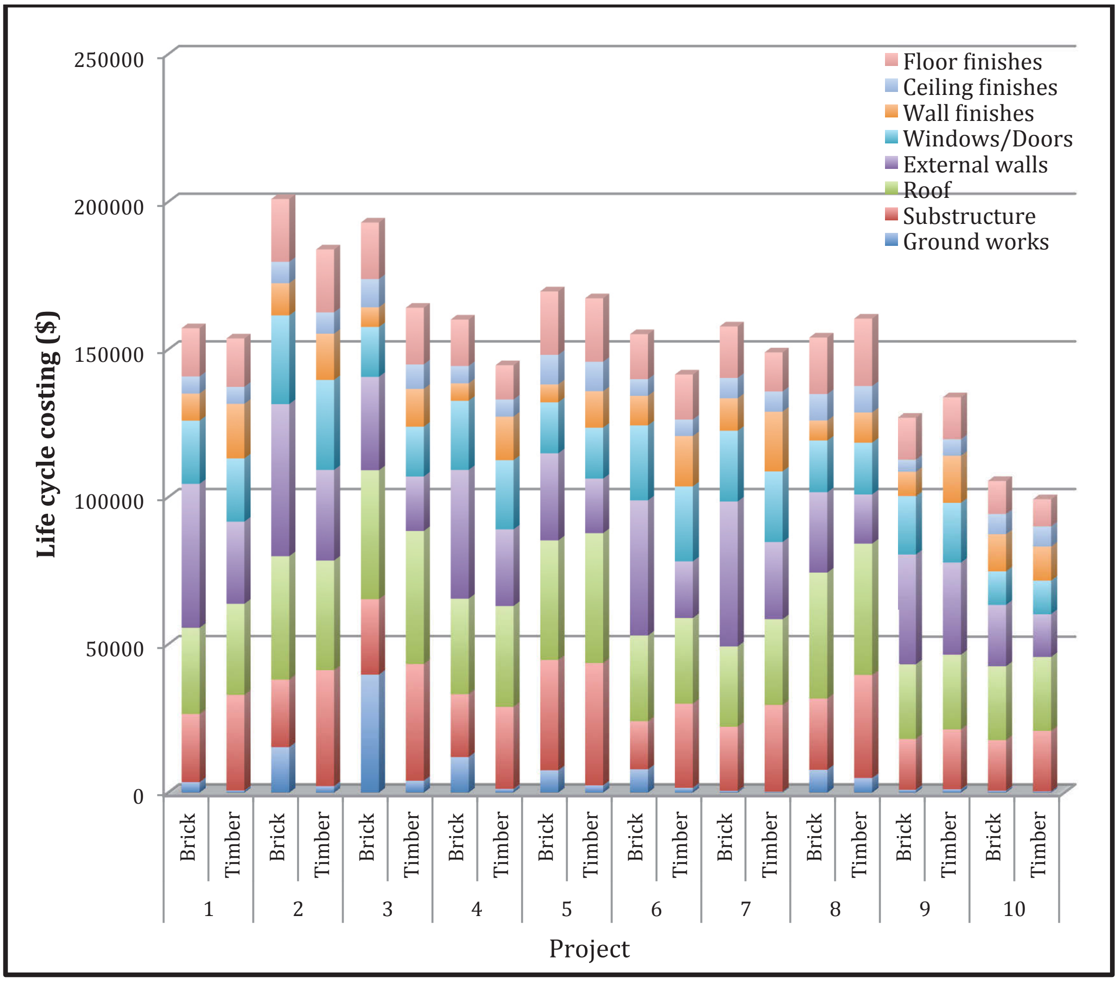


Figure 8.11 shows the distribution of costs through the different building elements. The wide range in the ground works is related to the requirement and size of retaining walls and extent of excavation activity. Substructure costs vary according to the footprint and slope of the land. Projects with smaller footprints expended less cost on reinforcement, formwork and concrete than the projects with large building footprint and also had lower roofing costs. As expected, the two-storey homes with larger external walls were greater in cost than single-storey homes and window and door cost were proportionate to the surface area of glazing/doors. The element cost breakdown in Figure 8.11 also shows that ground works is greater in the brick homes, which is most likely related to cut and fill and retaining structure activities. Project No.3 stands out due to a large amount of cut and fill and associated soil retention structures. Timber homes have limited cut and fill and soil retention however there is significant material and labour costs in installing concrete pad footings, above ground piers, bearers

and joists and fibre cement sheeting. This explains the greater cost for timber substructure over brick in every project. The other result that stands out is the significant external wall cost for a brick veneer system that is significantly greater than the timber clad/timber structural wall envelope. Wall finishes is more expensive for timber due to external painting of cladding and architraves. In summary, the main cost elements that had the greatest influence on total cost are the substructure, walls and roof.

LCC comparison data analysis for the ten projects has been undertaken and the first cost comparison in Figure 8.12 compares total life cycle costs.

Figure 8.12 Total life cycle cost comparison between timber and brick for 10 projects

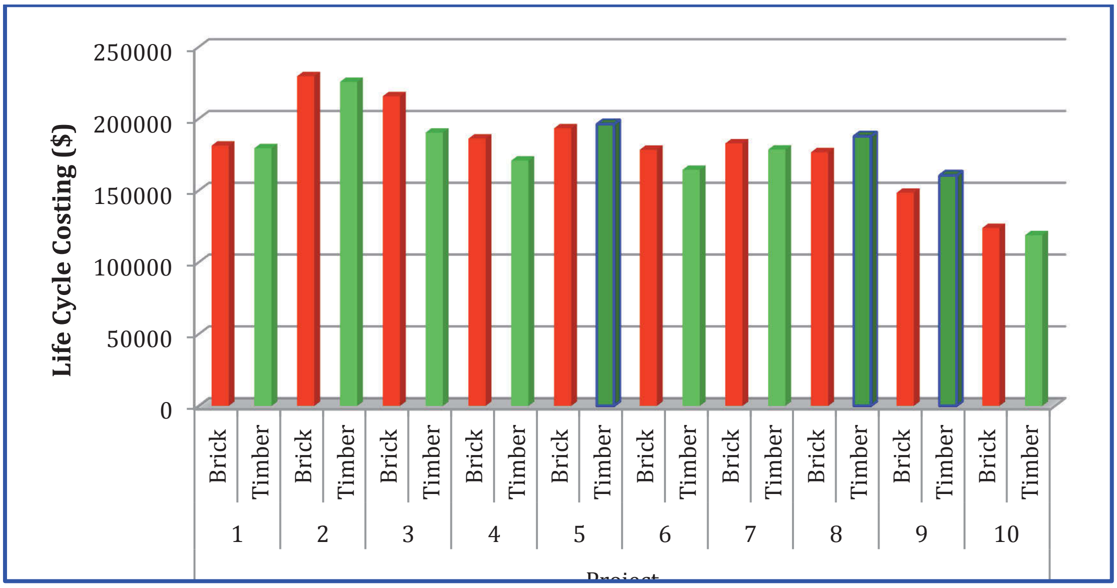
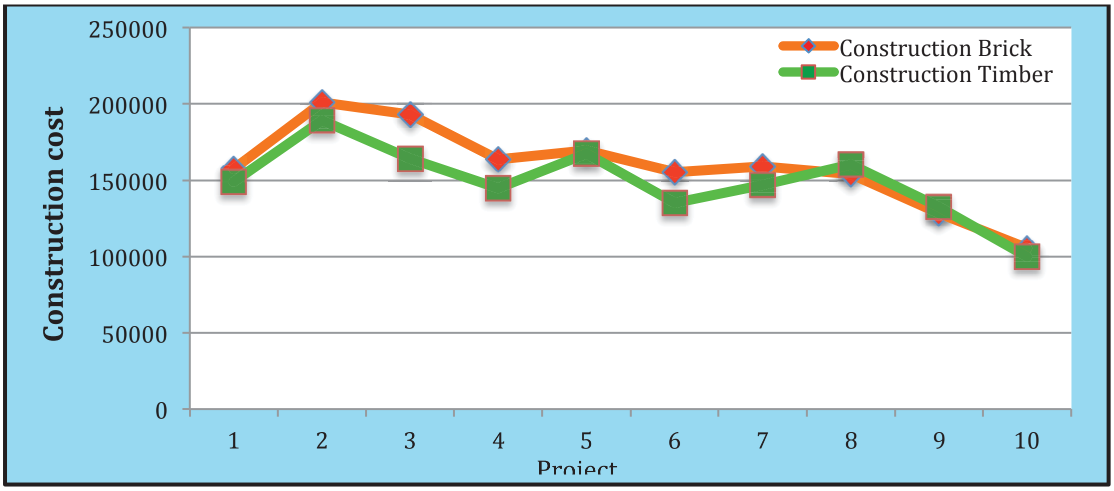


Figure 8.12 shows that seven of the ten brick projects were more expensive than timber projects over the life cycle period of 50 years with the difference ranging from 0.13% to 13.32% with a mean of 5.73%. The three timber projects (highlighted in blue) that performed worse than brick were Projects 5, 8 and 9 and these were two single-storey homes and one double-storey home. Further investigations of cost include the phases of cost, GFA correlation, and breakdown of cost per element. Figure 8.13, 8.14, and 8.15 show the comparison of costs in the construction, maintenance and end of life phases.

Figure 8.13 displays the construction phase of the case projects and demonstrates that all but two projects (8 and 9) had greater costs for brick.

Project 8 was 4.15% less than the timber alternative and Project 9, 3.35% less than the timber option. The difference between the other eight brick and timber homes ranged from 1.39% to 17.59% with a mean of 9.09% ($13519) less for timber.

Figure 8.13 Construction cost comparison between timber and brick



Maintenance costs were greater for timber in all projects as shown in Figure 8.14 with a mean difference of 27.38%. This disparity is likely to be found in the costs associated with the replacement and painting of the external timber cladding. The timber cladding and painting costs were a significant part of the cost of maintenance for the timber projects.

Figure 8.14 Maintenance cost comparison between timber and brick

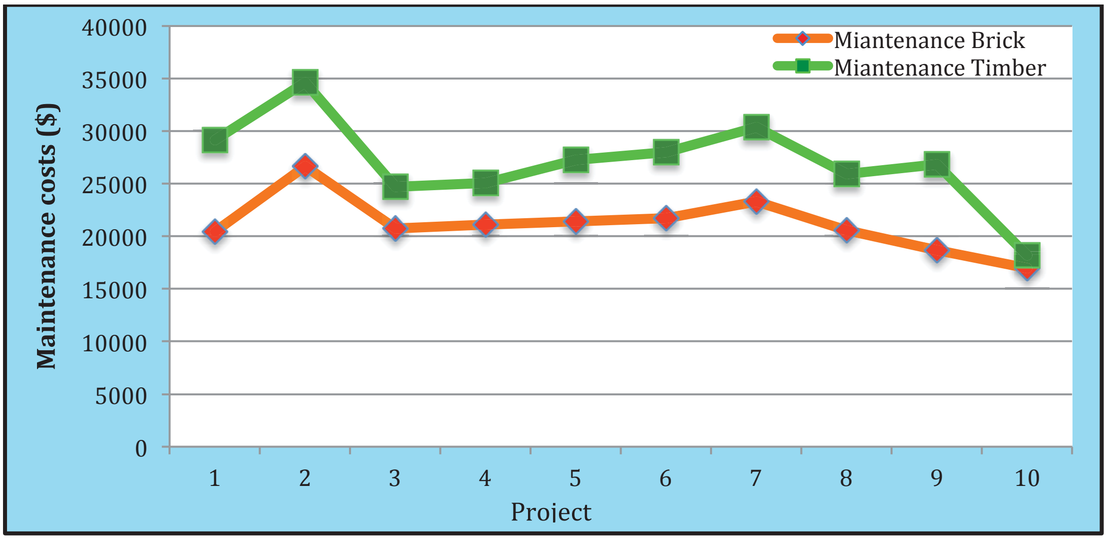
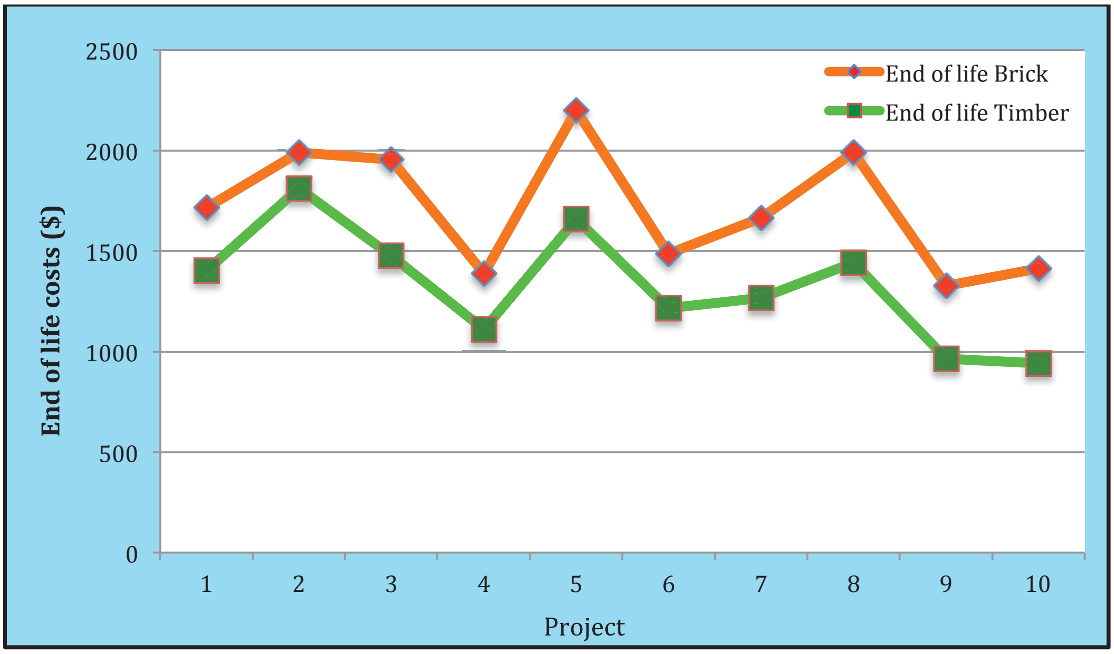


Figure 8.15 reveals a clear distinction between timber and brick end of life costs with brick showing on average 30.14% greater costs for demolition and disposal. These additional costs are associated with additional uses for plant to demolish brick and concrete and by weight of waste for disposal at waste and resource centres. Plant hire for demolition is charged by the hour and construction waste by the weight.

Figure 8.15 End of life cost comparison between timber and brick



The final cost analysis in Figure 8.16 compares total LCC against GFA for timber and brick homes. Figure 8.16 shows the general upward trend of LCC increasing with larger GFA for both designs. The three projects distorting the trend are the single-storey homes that have a less efficient cost to GFA ratio when compared to double-storey properties. The largest home in terms of GFA has other factors adding to its cost per area, including a lot of slab edge beams and a particularly large area of wall envelope. These both relate to the way the house has been designed to deal with the site slope.

Figure 8.16 Timber and brick correlation between life cycle cost and gross floor area

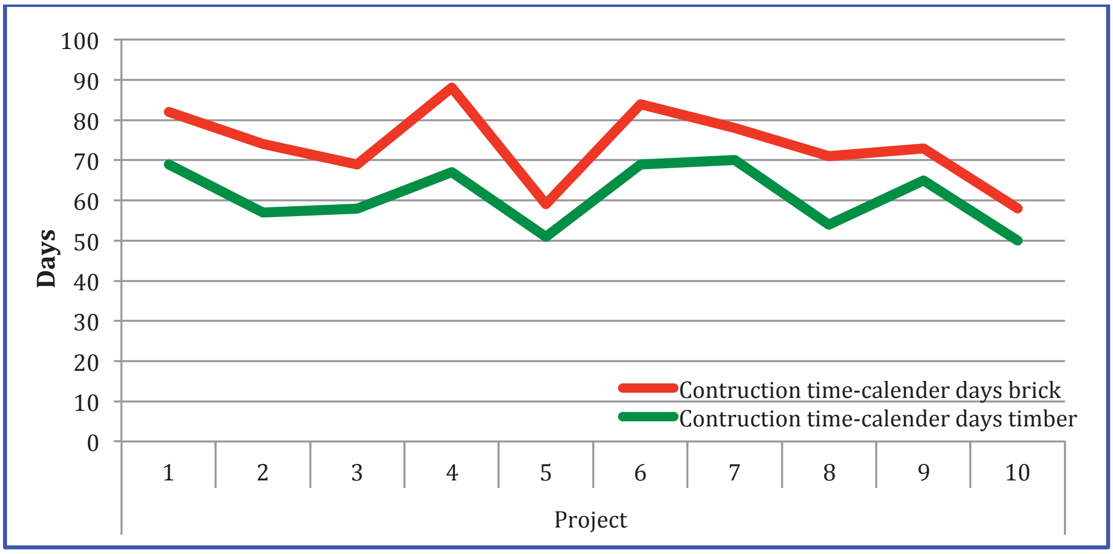
This finalises initial life cycle cost (minus operating energy) analysis that establishes that brick homes were more expensive in seven of the ten case studies by 5.73% with most of the additional cost found in the ground works and wall envelope. Substructure costs for timber are more expensive in every project related to the labour and materials required in this process. Maintenance is significantly greater for the timber homes (27.38%) due to cladding replacement and painting and end of life costs larger (30.14%) for heavy material homes. A trend of increasing LCC with increasing GFA is supported by data with the exception of single-storey homes. The next section compares the time of construction for the particular case study projects.

8.5.4 Case study project optimised schedules - Timber v Brick

The two designs were also analysed and compared for time. The analysis was focused on construction time only as discussed before. The approach was to calculate times for trade activities and their overlap and compare the differences using heavy materials and timber using current trade practices to establish which was more efficient. Some activities such as kitchen and bathroom installation would be the same in each type of construction so these were excluded. However if the activities before, during or after these activities were different, (e.g. floor preparation for the bathroom) the time impact of these activities were counted. The analysis addressed the wall and floor structures in particular, as this is where the most significant differences are between the timber and heavy material structures. Time of construction is measured in calendar days.

The construction times for both brick and timber designs were presented in Figure 8.17 that shows the numbers of working days for each project and compares timber and brick times.

Figure 8.17 Construction schedule. Comparison between timber and brick



The main areas of difference between the brick and timber projects occurred in the set up, coordination between trades, and completion of the concrete slab and brickwork. The projects with large concrete floor slabs with a number of drop edge or deep internal beams resulted in more time taken to complete the floor structure. This time increase is related more extensive detailed excavation, formwork and reinforcing placement. Concrete floor slabs also have the delay of the waste plumbing installation before the slab can be poured whereas the plumbing in the timber homes doesn't conflict with footing installation. Bricklaying time and the dependencies around its completion are not as integrated as with timber envelope. Timber cladding times ranged from 3-5 days compared to brick that had minimum completion time of 8 days with a maximum of 17 days for the largest home.

An analysis of the time per the gross floor area showed no relevant correlation so a comparison of the area of brick envelope to construction time was conducted. This is displayed in Figure 8.18.

Figure 8.18 Construction schedule compared to area of wall envelope (m2)

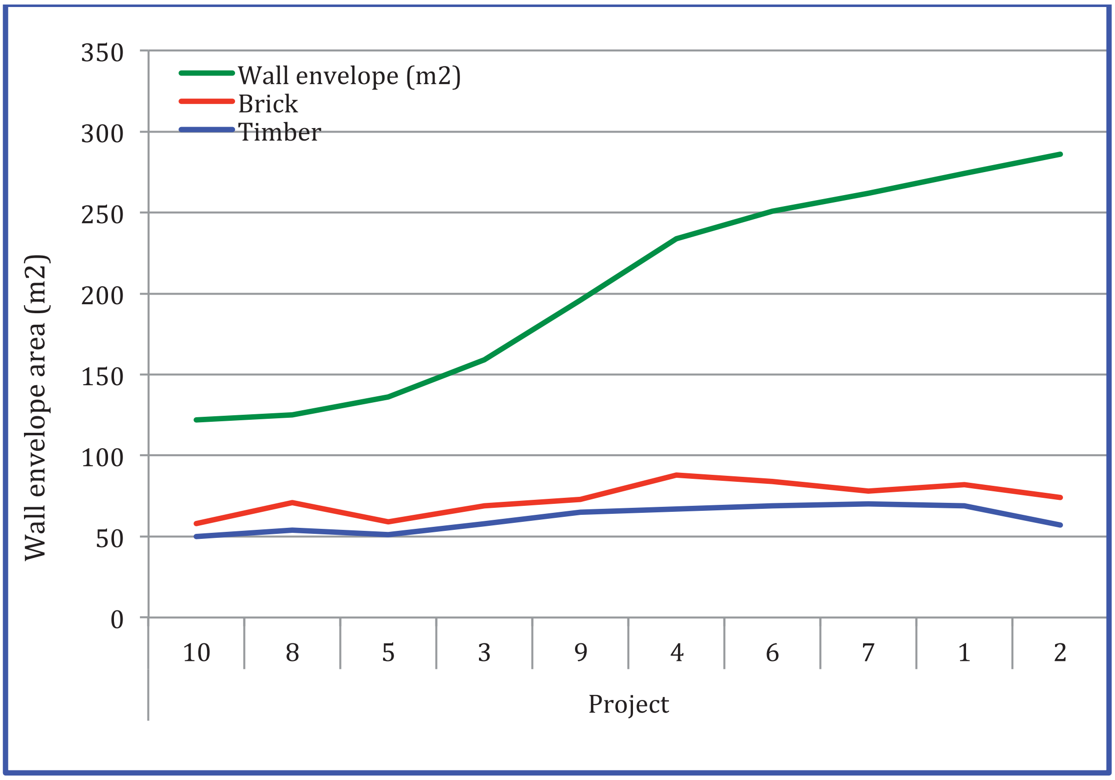


Figure 8.18 shows a slight positive increase in time of construction as the area of brick envelope increases. However, there appears to be a point (around 240m^2 of brick) at which the projects cease to be negatively affected by a larger wall envelope area. Other factors such as ground works and substructure area could also have an increased impact. To check the impact of the substructure on the construction time the footprint is measured against the schedule and this is reported in Figure 8.19.

Figure 8.19 Construction schedule compared to building footprint area

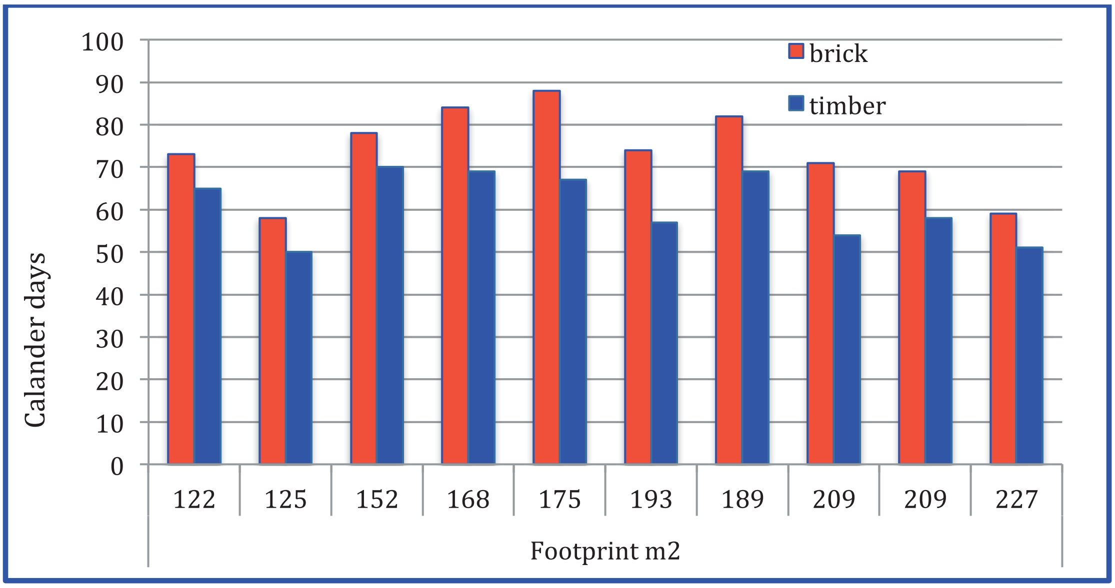


Figure 8.19 shows an increase in time as the footprint of brick homes rises to a point (175m^2) and then decreases. The decreasing times for the larger footprint could be associated with the reduction in brick area for the single storey homes. The timber homes showed less variation in the number of days for the varying footprint. Single storey homes with larger footprints than two storey homes were quicker to erect despite the floor structure size increasing. This may be due to most work being on ground level. Both brick and timber two storey homes require scaffolding for the wall envelope that reduces the efficiencies of both bricklaying and cladding installation. Further research with larger numbers of projects would be beneficial to see more definitive trends associated with footprint and envelope area of concrete and brick projects. The only conclusive analysis for time established in this section is that timber construction is quicker than heavy materials and this confirms the opinions of construction professionals during the interview phase of this research. The next section investigates the initial findings that timber has superior performance in the area of life cycle cost, life cycle energy and construction speed than brick projects. Statistical analysis is used to confirm the initial results.

8.6 Analysis of the relationship between timber performance and brick performance in housing

8.6.1 Introduction

The analysis to this point established that thermal performance of brick and timber projects could be achieved through changes to the building envelope. It also showed that, based on the thermal equivalent redesigned timber project, the performance in terms of LCC, LCE and time was more efficient than the original brick case projects. The following sections will examine the degree of association between the performance of timber and brick based on metres squared gross floor area (GFA) (m^2). Regression analysis and correlation were used to measure the degree of closeness between the two types of construction as GFA changed. The analysis will determine if there is consistently higher performance of timber when compared to brick based on (GFA) (m^2) for time, cost and energy use.

8.6.2 Analysis of the relationship between life cycle cost of timber and brick per m^2 gross floor area

Table 8.15 shows the regression analysis results for the LCC of timber per m^2 GFA and the LCC of brick per m^2 GFA. The coefficient of correlation is quite high ($R=0.96$) indicating a very close relationship between the two variables. To explain the number of variations in the dependent variable Y (timber LCC m^2 GFA) explained by the variations in the independent X (brick LCC m^2 GFA), the coefficient of determination is examined. The coefficient of determination is (R Sq. = 0.92) which shows that 92% of variation in the LCC of timber homes is related to changes in the brick LCC.

Table 8.15 Regression analysis results for LCC comparing timber to brick by m^2 GFA

Regression Statistics						
Multiple R	0.96264					
R Square	0.92668					
Adjusted R Sq	0.91751					
S	59.9936					
No. observations	10					
ANOVA						
	d.f.	SS	MS	F	p-level	
Regression	1	363936.21	363936.2191	101.1149202	8.14391E-06	
Residual	8	28793.86	3599.23361			
Total	9	392730.08				
	Coefficients	Standard Error	t Stat	p-level	Lower 95%	Upper 95%
Intercept	61.4776	76.99889	0.798422613	0.44767675	-116.0821188	239.037
Brick	0.90121	0.08962	10.05559149	8.14391E-06	0.694539539	1.107880

This means that as the LCC of brick homes increases, the timber redesign LCC will increase but by a proportionally reduced amount. In order to explain the cost relationship, the straight linear regression model can be used and the linear regression equation for timber LCC and brick LCC is:

$$Y = 0.9012x + 61.4777 \quad (4)$$

where Y is the LCC of timber per m^2 GFA and x is the LCC per area of brick in m^2 GFA. Figure 8.20 shows the graphical representation of this equation for the ten projects.

Figure 8.20 Straight-line regression equation for timber and brick LCC per m² GFA (excludes use phase)

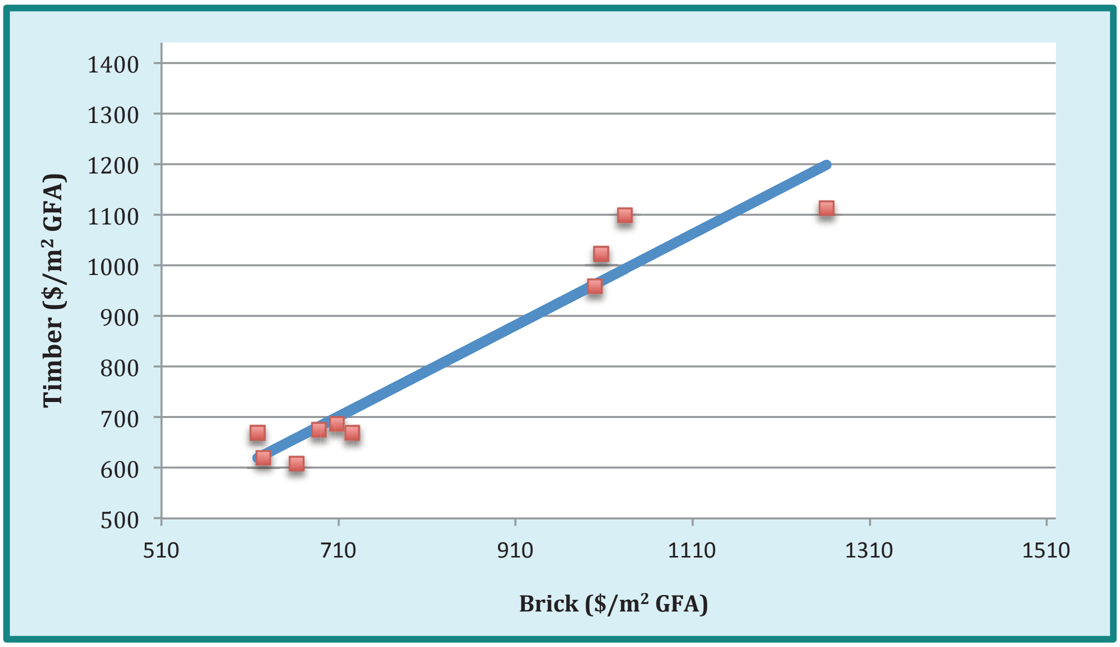


Figure 8.20 shows the placement of timber projects around the linear regression equation. This blue line represents the relationship between the cost of timber and brick and can be used to forecast the LCC of any timber based on the LCC by m2 GFA of an existing or proposed brick home. As can be seen on the graph, the timber projects are cheaper than brick over its life cycle of 50 years. (For example, a brick project costing $710 per m2 would cost $700 per m2 over 50 years if constructed with timber.)

8.6.3 Analysis of the relationship between life cycle energy of timber and brick per m² gross floor area

Table 8.16 displays the correlation between life cycle energy of timber per m² GFA and the life cycle energy of brick per m² GFA through the results of regression analysis. The coefficient of correlation is close to +1 (with a result of R=0.99) indicating an almost perfect relationship between the two variables. The variations in the dependent variable Y (timber LCE m² GFA) are almost all explained by the variations in the independent X (brick LCE m² GFA). The coefficient of determination result is (R sq. = 0.98) which shows that 98% of variation in the LCE of timber homes is related to changes in the brick LCE.

Table 8.16 Regression analysis results for LCE comparing timber to brick by m² GFA

Regression Statistics						
Multiple R	0.9950					
R Square	0.9900					
Adjusted R Square	0.9888					
S	97.8905					
Total number of observations	10					
ANOVA						
	d.f.	SS	MS	F	Signif. F	
Regression	1	7626603.315	7626603.315	795.8838987	2.69266E-09	
Residual	8	76660.46093	9582.557616			
Total	9	7703263.776				
	Coefficients	Standard Error	t Stat	p-level	Lower 95%	Upper 95%
Intercept	121.1778516	304.5023577	0.397953738	0.701072807	-581.006	823.362
Brick (x)	0.896058188	0.031762257	28.21141433	2.69266E-09	0.823	0.969

The coefficient of determination of 0.98 demonstrates that the LCE of timber projects will rise correspondingly to an increase in the size of brick homes and the timber LCE will decrease proportionately to decreases in the area of brick GFA. The amount of LCE for timber will be consistently lower than brick for the same size home. This relationship is expressed by the linear regression model and this linear equation for timber LCE and brick LCE is:

$$Y = 0.8961x + 121.1779 \qquad (5)$$

where Y is the LCE of timber per m² GFA and x is the energy (MJ) per area of brick in m² GFA. Figure 8.21 shows this linear equation and the proximity of the ten case study projects to the regression line.

Figure 8.21 - Straight-line regression equation for timber and brick LCE (MJ) per m² GFA (excludes use phase)

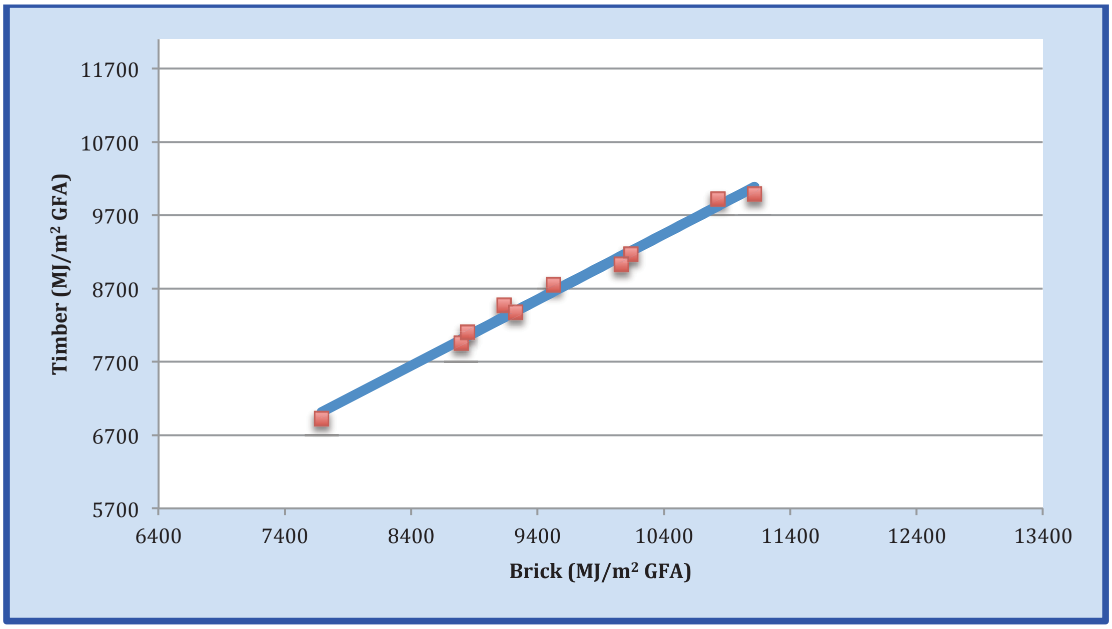


Figure 8.21 displays the line of regression, which allows for forecasting of LCE for timber projects based on the LCE of brick projects per m² GFA. The proximity of case study projects (red dots) shows the close the relationship between the two variables. The regression equation also demonstrates that for every square metre GFA of a brick project, a timber home with the same GFA will have less life cycle energy. This is demonstrated on Figure 8.21 where a brick design using approx. 9400MJ over a 50-year period can be replaced with a timber home with the same GFA m² and use close to 8700MJ per m².

8.6.4 Analysis of the relationship between time of construction of timber and brick per m² gross floor area

Table 8.17 displays the correlation between construction time of timber homes per m² GFA and the construction time of brick homes per m² GFA through the use of regression analysis. The coefficient of correlation is high with a result of (R=0.98) indicating a near perfect relationship between the two variables. The coefficient of determination result is (R sq. = 0.95) which shows that 95% of variation in the construction time of timber homes is related to changes in the construction time of brick homes based on the area in m² GFA.

Table 8.17 Regression analysis for construction time comparing timber to brick by m^2 GFA

Regression Statistics						
Multiple R	0.9772					
R Square	0.9549					
Adjusted R Square	0.9493					
S	0.0139					
No. observations	10					
ANOVA						
	d.f.	SS	MS	F	p-level	
Regression	1	0.0329	0.0329	169.5743	1.1473E-06	
Residual	8	0.0016	0.0002			
Total	9	0.0344				
	Coefficients	Standard Error	t Stat	p-level	Lower 95%	Upper 95%
Intercept	-0.0041	0.0220	-0.1872	0.8562	-0.0550	0.0467
Brick (x)	0.8526	0.0655	13.0221	1.1473E-06	0.7016	1.0035

The coefficient of determination of 0.95 shows that as the time for construction rises per m^2 GFA, a timber home with equivalent design will also increase although it will remain consistently faster to build than brick. The speed at which the alternate timber home can be built can be determined by inputting the time for the brick home per GFA into following linear equation:

$$Y = 0.8526x - 0.0041 \qquad (6)$$

where Y is the time in days for timber construction per m^2 GFA and x is the time for construction per area of brick in m^2 GFA. Figure 8.22 shows this linear equation and the proximity of the case study projects to the regression line.

Figure 8.22 Straight-line regression equation for timber and brick construction time (days) per m² GFA

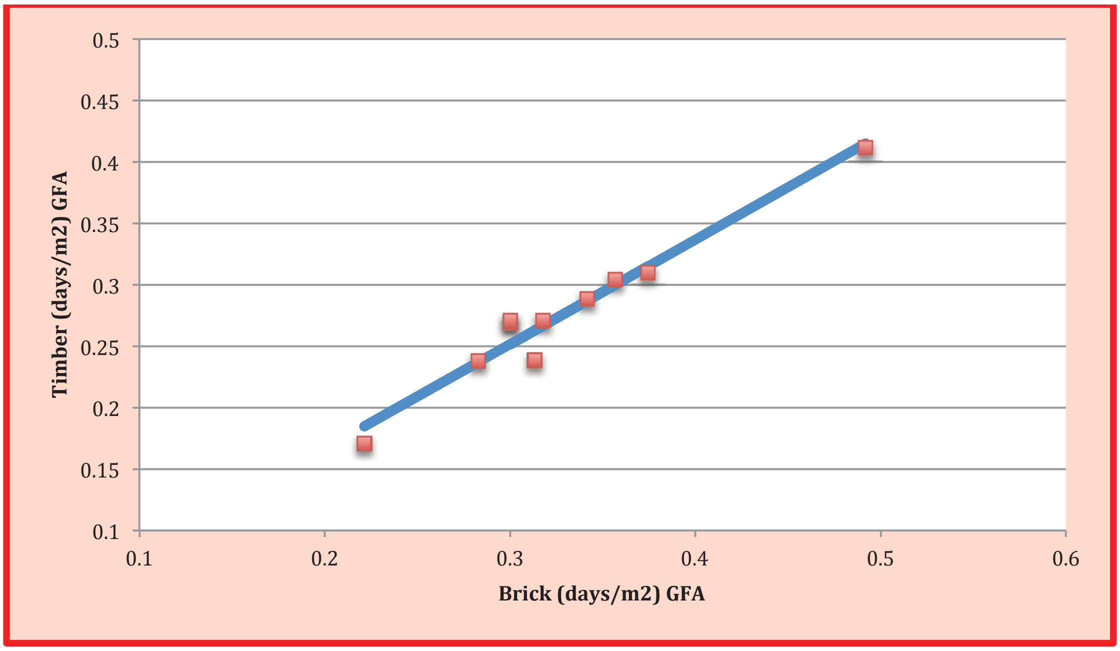


Figure 8.22 shows the closeness of relationship between timber construction time and brick construction time that was numerically reported in the coefficient correlation. Predicting the timber construction time can be done accurately through using the formula of the regression line or estimated by the line depicted on the graph. For example, for every 0.3 days taken to build a m^2 GFA of a brick house it will take close to 0.25 days for the timber design.

In summary of this section, the statistical analysis using regression analysis demonstrates a strong relationship between the performance of timber and brick when compared according to gross floor area in metres squared. Results showed that timber requires less time for construction, less cost and has a lower energy burden over the lifetime per m^2 in the homes analysed.

8.7 Case study results and validation of the sustainable residential development model

The sustainable residential model developed in Chapter 7 and shown in Figure 7.6 identifies the four main criteria required for sustainable residential developments. These were derived from the literature, current residential development client value offerings, questionnaire surveys and interviews with construction practitioners. The four criteria are time, cost, quality and sustainability. The model was verified by using timber as the alternative to the current heavy material design. A life cycle perspective was taken in order to consider the flows of materials over the building's life span. This perspective is in keeping with the literature on sustainability in construction projects that considers energy used to produce buildings, the energy used in the operation of buildings and in the disposition of the materials at the end of the building's life. The following subsections will discuss how timber performed against the primary criteria of the sustainable residential development model.

8.7.1 Quality performance of timber

The sustainable residential development model lists two main aspects of quality in residential construction projects that are design related measures and user comfort. Under the design theme, fire, acoustics, aesthetics, insect resistance, maintenance, structural performance and durability are subthemes. Building legislation and the detailing by design professionals dictate these subthemes. These subthemes are more pertinent to multi-residential construction and should be tested as part of further research. User comfort is the other major theme of quality and thermal performance was addressed in the testing of the timber design that was implemented in the sustainable development model. Due to the testing of timber being compared against the heavy material model, the timber cases were designed with thermal ratings as close as possible to those of the brick case studies. This allowed for the testing of the sustainable development model using time to be undertaken on an equal thermal performance to the current heavy material designs.

8.7.2 Cost performance of timber

The sustainable residential development model separates cost performance into four stages that is design, construction, operating and maintenance, and demolition/disposal costs. The heavy material linear approach to residential building projects focuses only on the construction costs and therefore has minimal regard for ongoing costs or the demolition and disposal stage. The case studies in this research tested the cost for timber alternate designs in the construction, operation and maintenance, as well as the demolition and disposal stage of the building life cycle. The initial results showed that timber life cycle costs are on average 2.4% per m^2 less than brick cases over the 50-year period. The breakdown of cost over the life cycle stages resulted in the construction cost of timber being 6% per m^2 less than brick although the maintenance cost of timber was 23% per m^2 greater than brick over the 50-year period. (It is noted that use phase is excluded from these calculations).

This result does not account for industry efficiencies and increased durability of timber products and external wall finishes that will reduce maintenance costs once they are introduced into the market. End of life costs for brick were 14% per m^2 more than timber due to the additional heavy plant required and disposal costs related to the concrete slab and brick envelope. Regression analysis on LCC showed that the use of timber in the SRD model resulted in a $10 per square metre saving when compared to the current heavy material model using brick. Whilst these results validate the SRD model by demonstrating that the sustainable timber model is cost efficient compared to the heavy material model the difference is not significant.

8.7.3 Sustainable performance of timber

Four energy contributors are accounted for in the SRD model: operating energy, embodied energy, demolition and disposal energy. The current heavy material model focuses on reducing operating energy through energy efficient light fittings and thermal conditioning systems. The SRD approach to sustainability is on reducing energy over the life span of the building. Validating timber as the more sustainable material compared to brick projects was achieved through measuring the embodied energy, maintenance energy and end of life energy.

Energy for thermal conditioning was omitted as these were assumed to be the same due to the thermal design and thermal star ratings achieved through thermal analysis. The average energy consumption of the life cycle stages was mainly consumed in the construction and maintenance phases, with 54% and 45% respectively, and with just 1% energy used at the end of life for demolition and disposal. In the construction phase, brick was found to have 18% more embodied energy than timber.

Timber projects on average were more energy intensive to maintain by just 2% but a lot less than brick by the end of its life (58%). Regression analysis demonstrated that there is a high correlation between the LCE of brick and timber, which means that changes to the size of the brick home (affecting LCE) will result in a change in the LCE of a timber home with the same design. This change is directly proportional and so, given the m^2 LCE of a brick building, it is possible to predict that a timber building of the same design would result in close to 90% of the LCE of the brick design. Other factors may affect these results such as slope of land, soil and extreme climate areas and are discussed in further detail in Chapter 9.5.

8.7.4 Time performance of timber

The SRD model breaks the time components of a residential building project into the design development phase, construction phase, operating phase and demolition phase. The design development phase is zero or minimal for volume home projects because the designs have already been fixed and generally allow for only minor changes by the client at maximum cost. Therefore the time for design development has been omitted from the case studies. The operating phase has been identified as 50 years and this does not change between the brick and timber case studies. The demolition is currently quicker for timber due to the reduction separation of steel reinforcement from concrete.

The focus of the case studies was the construction schedule that showed that timber redesigned projects would be quicker than brick in all cases by a range of

8-15 days per project. The regression analysis showed that for the case studies one square metre of a timber home would take 0.85 days for every day it took for a brick home to be constructed. Time was viewed as critical to cost savings by the majority of construction practitioners interviewed due to the increasing cost of labour, site establishment and running costs, and the supervision of safety. Timber prefabrication has the potential to further reduce construction time and will be discussed further in Chapter 9.6 as an idea for further research.

8.7.5 Confirmation of initial propositions of timber performance

The traditional lineal residential construction model is based on achieving the key performance criteria in construction project management that are time, cost, and quality. Sustainability is only considered in the linear model where required by legislation and focuses just on operating energy. The lineal model is based mainly on outcomes in the initial phase of a buildings life, which is the construction phase. This brings some problems with this lineal model that include the following.

- The current model is dependent upon heavy materials that use natural resources in large quantities that once have been removed from the ground will not be replaced.
- There is high-energy use required to dig up, transport, smelt, refine, and manufacture the raw materials for use in bricks, mortar, steel reinforcing and concrete. This results in residential properties that have high-embodied energy. This is not a consideration of the lineal model.
- Lack of consideration of the end of life scenario for the buildings. Reinforced concrete and bricks with cement mortar require energy intensive destructive methods in the demolition process. There is currently no requirement or process that encourages construction for disassembly.
- Slow methods of construction are the basis of the heavy material. The use of concrete in floor structures requires time consuming excavation, formwork and finishing process. Likewise brick laying is a slow process

that leaves minimal opportunities for additional time efficiencies. The lineal model lacks innovative processes to encourage change through use of new materials or construction methodologies.

- Cost efficiency constraints are another issue with the current model as it has achieved already a lot of efficiencies through construction techniques and methods using the current heavy construction materials

The sustainable residential development model provides a number of benefits over the traditional lineal model due to it taking a life cycle approach and a consideration of the end of life scenario for residential construction materials. In particular, the SRD places emphasis on environmental sustainability of homes without reducing the importance of the other key performance factors for construction as listed below.

- The SRD model using timber involves minimising the use of non-renewable materials by maximising timber in the housing projects. This reduces negative impact on the natural environment and landscape. It also allows the land used to grow the material to return to its original state or be used for further material production. This is not possible with the lineal model.
- The SRD model using timber reduces the embodied energy in the final housing projects, as it is lighter to transport and requires less energy intensive processing than heavy materials.
- The end of life plight of materials in the SRD model are considered and allow for recycling and reuse with less energy and equipment than the materials in the linear model. Additionally, there are greater end of life use for timber after it has completed it’s life cycle journey. It can be reused in other timber projects, recycled into woodchips and other composite products or burned to produce heat energy.
- The SRD model utilising timber as the main structural material allows for construction time savings through labour and supply efficiencies as well as prefabrication opportunities. It also offers construction time efficiencies through reduced installation of services in residential

construction. Finally, the SRD allows tighter trade coordination and scheduling not available to the lineal model.

- Cost reduction through the implementation of the SRD model using timber is possible through reduced quantity of materials and less transport costs. Reduced site costs and prefabrication opportunities also can provide cost saving benefits. Reduced management requirements can also produce cost savings through implementation of the SRD model using timber.
- Quality of the homes built using the SRD model can meet and exceed that of the lineal model. The thermal performance of timber as well as structural, insect resistance and durability can match or even exceed that of the lineal modelling using appropriate design techniques.

This discussion demonstrates that the SRD model has the potential to outperform the lineal model in time, cost and quality. It also shows that in regards to sustainability the SRD model using timber will reduce life cycle energy compared to the lineal model.

8.7.6 Comparing sustainable residential development (SRD) model with the traditional linear model

The propositions stated at the beginning of this Chapter in 8.2.1 were based on the sustainable residential development model developed in Chapter 7.6 and were used to verify the use of timber as a suitable alternative to currently used heavy materials on a life cycle perspective. The verification relied on a remodelling of ten existing brick and concrete homes into timber envelope homes that would exhibit the same thermal performance to allow for equitable comparisons of life cycle cost, life cycle energy and construction time. The results of this verification are:

1) The proposition that timber construction time is quicker than heavy material construction time has been confirmed. This was confirmed by comparing traditional home construction time with the timber

construction time. Schedules of ten traditional brick veneer homes with concrete floors were the basis of comparison. The timber-remodelled homes were analysed for schedule using current industry standard rates for trades and accounted for trade coordination. The results showed that timber homes were faster to construct in all cases. The importance of speed in construction was expressed by construction practitioners through the interviews in this study and the review of literature. Reductions of construction time benefit the construction company through site and management costs. It also provides advantage to developers and investors by speeding up the time in which buildings are sold, leased or occupied. If testing of the SRD did not demonstrate time benefits over the traditional model it would render the SRD less viable.

2) The proposition that timber life cycle cost is lower than heavy material construction life cycle cost has been confirmed. The cost over the life cycle of timber homes was confirmed to be less on average than the traditional homes when construction, maintenance and end of life scenarios were considered. Initial construction cost of timber was found to be less than brick as was the end of life costs. Timber maintenance was higher over the 50-year life cycle. Cost performance criterion is critical in the uptake of the SRD model due to the importance of cost in construction projects. Construction practitioners confirmed in the interviews that if timber residential development was the same or less than heavy materials it would be considered as an alternative. If timber were to be found more expensive in the construction phase it would not be proposed for residential projects.

3) The proposition that timber life cycle energy is less than heavy material construction life cycle energy has been confirmed. It has been confirmed through the analysis of embodied, maintenance and end of life energy of traditional homes and timber-redesigned options. The comparison of life cycle energy was less in timber homes than traditional in all the analysed cases. This demonstrates that there is a case for adopting the SRD model

using timber to reduce energy use in residential development compared to the traditional linear model. The importance of validating the energy benefit of the SRD model is central to the model as it focuses on increasing sustainability whilst providing the other project performance benefits.

These results validate the use of timber in the sustainable residential development model to achieve the main objectives of the Australian residential development sector. These objectives, as described throughout the thesis, are reduced carbon impact, increased time and cost efficiencies as well as controlling quality.

8.8 Conclusion

The chapter started by discussing the methods for choosing cases for verifying the sustainable residential model developed in Chapter 7.5. The propositions relating to timber were documented and verified using ten real life case studies by redesigning heavy material homes with a timber envelope to provide thermal performance equivalent to the brick projects. Various statistical methods revealed that a timber envelope can provide benefits over brick and concrete homes in the three categories of life cycle cost, time and life cycle energy. The results were clearly demonstrated with the life cycle energy and time although the life cycle cost comparison was less significant.

Construction cost reductions has been identified for timber in the criteria of materials, labour, plant, equipment, material delivery and waste in the literature. Materials are installed with greater speed and lighter equipment, and less plant is required and less labour needed for completion of the structure. In addition, the weight of material delivered is reduced and construction waste is lower than concrete or bricks due to weight. In addition, demolition and disposal of timber structures should be cheaper than the heavy materials because landfill is measured by weight. Recycling of timber requires less energy than concrete and bricks. The next chapter provides a strategy for implementing the sustainable residential timber development model in Australia's residential sector. It also provides a summary of this thesis, conclusions and further research opportunities.

Chapter 9 Implementing a sustainable residential model, further research and conclusion

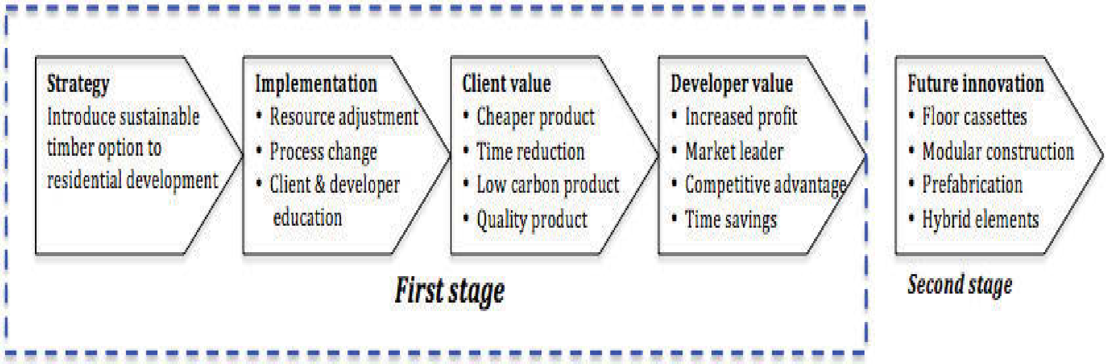
9.1 Introduction

Chapters 7 and 8 studied how the current model of residential development fails to address the changing requirements of the construction industry, which is to reduce its environmental impact and minimise use of non-renewable resources. Chapter 7 investigated the current residential development model based on heavy materials and proposed a sustainable development model using timber. Chapter 8 demonstrated that timber could be used to achieve the key performance criteria of construction projects (time, cost and quality). It has also showed that timber is a suitable material for a circular and sustainable construction model due to its low energy impact, and high renewable and reusable elements compared to traditional heavy materials. This Chapter will firstly discuss how implementing a sustainable timber residential strategy affects the existing construction model and its stakeholders. It will then provide a brief summary of the research and a review of the aims and objectives of the study. Finally, the chapter will consider some limitations of the research and recommendations for further research.

9.2 Implementing a sustainable timber residential development model.

Figure 9.1 displays a strategy for timber residential development and shows the business implementation requirements and the value proposition for clients and developers. The discussion will address the first stage only as the second stage of the strategy will be proposed as the subject of investigation for future research.

Figure 9.1 Proposed strategy for timber design options in residential development



The implementation of the new strategy will require changes to both internal processes and relationships with suppliers, subcontractors and clients. The current client value proposition in Figure 7.3 in Chapter 7 includes a fixed price for clients for an all inclusive product (turnkey), fixed quality and value for money. The benefit to the developer of a fixed price for limited design options is that they can procure subcontractors on a fixed square metre rate and can predict costs and profit margins. Any additional efficiency in the construction process are added advantages to the developer. This process is linear, as it does not include consideration of the operating or end of life scenario of the building or materials. If residential developers were to adopt a sustainable timber model they would need to change their current processes and modus operandi. Successful implementation is expected to result in increased construction speed, decreased costs and an increase in the environmental sustainability of their residential construction projects. The anticipated value for the developer is additional sales, increased profit margins and market leadership creating the opportunity to achieve competitive advantage.

Businesses need to adapt and adjust to business environment changes and opportunities through the reorganisation of their people, processes and physical capital in order to maintain competitiveness in their particular market (Pavlou & El Sawy 2011; Teece 2009). Some of the key resources and processes of the current residential developers' operations will need to change to cater for a sustainable timber residential design and these are listed below.

i) Key Resources

- Office staff taking enquiries will need to be educated on the differences between the concrete/brick option and timber design option and be prepared to respond to the common customer misperceptions of timber performance.
- Construction managers will have to adjust to different lead times for the timber and adjust material orders to suit. They will also have to field subcontractor queries and ensure construction quality is achieved until subcontractors have been adequately trained. A reduction in the time and type of scaffolding will need to be managed.
- A new set of designs will need to be procured and this process will require input from architects, engineers and carpentry and service trades in order to produce material, labour and time efficiencies in design.
- Subcontractors will have to be provided with new schedules for timber projects and they will need to negotiate new contractual agreements.
- New supply agreements will be negotiated with timber suppliers and there will be a reduction in excavation works. Allocation of trade responsibilities for pier holes, footing and piers will be required.

ii) Key processes

- A marketing and sales campaign will need to be established to inform the public of the new product/design with all the associated benefits. A display home would allow potential customers to experience the product prior to commitment.
- Contracts will need some minor adjustments in terms of project completion time and progress payments.
- Investigations will need to be undertaken into design compliance with the NCC in regard to energy efficiency (Part 3.12) and designated bushfire prone areas (Part 3.7.4) and Australian Standards (AS 3959). Other legislative requirements in NSW include BASIX certification and abiding by local government requirements. Working with and educating council

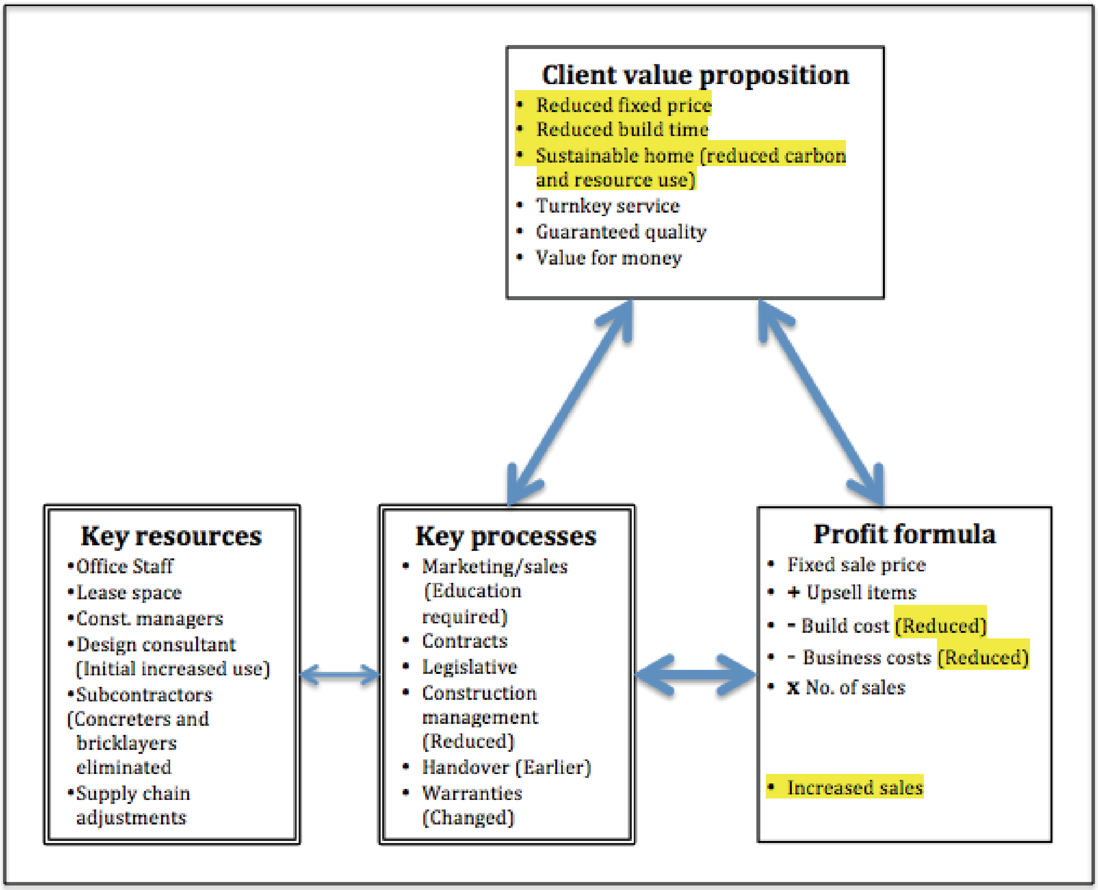
representatives and private certifiers will be needed to avoid conflict and delay.

- Construction management will initially require additional time to ensure subcontractors are coordinated efficiently until preferred subcontracting companies are trained in the new process although it is expected this will be reduced with the reduction of trades.
- Handover will be achieved more quickly although it will require the same attention to defects as a traditional residential development.
- Some additional consideration may be required about warranties relating to the durability of wall cladding and structure.

These are some of the changes that could affect the resources required and the operational processes of the current linear residential construction model based on heavy materials. The opportunity for increased value for both clients and developers is shown in the next section.

Changes have been made to the original residential development client value proposition model (Figure 7.3) and shown in Figure 9.2 to account for the influence of the implementation of the sustainable timber residential model. The boxes around the key business resources and processes have been surrounded in double lines to represent that changes are required in these business model components and yellow highlighted sections represent the increased value to the customer and developer by implementing the new sustainable strategy.

Figure 9.2 Client value proposition based on a sustainable timber residential model



Source: Adapted from Carroll 2012

Figure 9.2 contains the revised client value proposition for residential developments that incorporates sustainability through the use of timber to reduce the embodied carbon and reduce the use of finite resources by replacing most of the heavy materials (concrete, brick and steel) with timber elements. In addition to the increased value to the homeowner in the form of sustainable materials, a reduction of cost and time is expected for the same thermal performance of a concrete and brick residence. Benefits for the supply side are anticipated in the reduction of construction costs and building operation costs through reduced supervision, trade coordination and time, all due to material and labour supply efficiencies. This sustainable development model would need to be tested by individual businesses in their own test cases. (This could be the topic of future research.) Prefabrication is also an opportunity for increased efficiency using timber although this is not the focus of this thesis and is also mentioned as a future research opportunity later in this chapter. This concludes the discussion on implementing the sustainable residential development model in the Australian construction market. The following sections provide a summary of this research, a review of its aims and objectives, some limitations to it and, finally, some recommendations for further research.

9.3 Summary of research

The initial review revealed misperceptions of timber performance from both the demand and supply side of residential development and a number of barriers to and opportunities for increased timber use in the Australian residential market. These barriers and opportunities centred around the traditional model of residential development that is based on heavy materials and takes a linear approach to material use and resources. The final part of the review looked at some of the existing studies on sustainability in residential development and the tools used to access sustainability in these studies. The literature review highlighted a few topics that warranted further investigation. These include the perception of timber as a sustainable building material, the opportunities for and barriers to timber use in the Australian residential development sector, and the traditional model of residential construction.

Survey questionnaires were conducted with homeowners in Sydney, Australia. The questionnaires had participants from two different groups, the first had construction experience or a background in the industry and the second had no background or experience in residential development. This questionnaire discovered that homeowners would like to see an increase of sustainable materials in housing and that timber was considered sustainable by a majority of survey participants. However, the survey also revealed that the perception of the poor performance of timber would reduce the likelihood of increased uptake of timber use. These perceptions were based on past negative experience or misperception rather than on the actual performance of timber. The performance characteristics of timber that received negative appraisal in the survey were fire, thermal, maintenance, insect susceptibility, acoustics and durability. These opinions from the demand side of residential development were used as the basis for conducting interviews with construction practitioners to see if the designers, managers and constructors of residential buildings also carried these perceptions. The interviews were also used to identify the particular barriers to the Australian construction industry increasing it use of timber and some of the opportunities that increase might offer.

Semi-structured interviews with construction practitioners in Australia revealed that the supply side carried some of the misperceptions of the demand side although they focused more on the performance issues when discussing barriers to increased timber use. Whilst achieving legislative compliance for fire, acoustics, durability and thermal performance was considered as reasonable challenges to increasing timber use, they were not the main issues. The greatest concern for practitioners is whether timber residential developments could compete with traditional materials on cost, quality and time. A high majority of practitioners agreed that timber was more sustainable than the current heavy materials but this was secondary after achieving the primary objectives of project success (time, cost and quality).

Evidence of the adoption of sustainability into the current residential business model was limited in the literature and research on business innovation in the construction sector is minimal. This is due to the challenges of change in the industry, especially the complexity of the interactions of players in the industry and one off projects that reduces efficiency opportunities. A representative model for traditional residential development was developed from information collected from volume residential builders and based on the generic client value proposition model proposed by Carroll (2012). The traditional residential development model is linear and does not account for the sustainable use of materials over the life span of projects. It focuses on efficient use of heavy materials to produce outcomes based on profit and fixed quality. Consequently, a sustainable residential material model was developed using timber to account for the circular flow of materials through the life cycle of projects. The objective of this model was to reduce the energy impact of residential developments compared to the current linear model on the basis of a 50-year life cycle. The focus was on increasing sustainability whilst improving the time of construction, reducing the life cycle cost and providing equivalent or greater quality.

Ten Australian case studies were used to test the model on the basis of life cycle energy, life cycle cost and construction time. The ten cases used data from the completed buildings and a redesigned timber alternative with equivalent thermal performance was tested. Life cycle energy was calculated for a 50-year period taking into account the energy used for construction, maintenance, and end of life demolition and disposal. Life cycle costing also allowed for construction, maintenance and end of life costs. Construction time was analysed and compared to test the benefit of the sustainable timber option as part of the sustainable model. Statistical analysis was then conducted as further evidence of the benefit of the sustainable timber option compared to the traditional heavy material model. The ten case studies confirmed that the sustainable residential development model was shown to be advantageous over the traditional model in the areas of sustainability, time and cost.

A strategy for implementing the sustainable development model in the Australian construction industry was discussed and revealed that changes to processes and system and supply chains would be required to the current procurement method for housing. The costs and impacts to business to implement these changes were not part of the scope of this study, however, and could provide further research opportunities.

This research has contributed to the body of knowledge on the sustainable use of timber in residential development. No other study to date has looked at changing the traditional heavy material model to accommodate sustainable timber use in residential development to provide benefits in all the key performance areas of the construction industry. Through the use of survey questionnaire, interview and building case data, this research has been able to fill a gap in the knowledge around how to reduce life cycle energy requirements and limit the use of finite resources for residential development through the use of timber in lieu of heavy materials. A strategy was proposed to implement the sustainable development model within the current residential construction market.

In order for the proposed model to become a reality, the misperception of both the supply and demand side of residential development needs to be educated in the actual performance of timber. System efficiencies also need to be developed by industry to capitalise on the opportunities presented by the use of timber structures. This could include the use of prefabricated building envelope elements, supply chain reorganisation and construction methodology innovation. These are all topics for future research discussed in section 9.6.

9.4 Review of aims and objectives

This thesis outlined a number of aims and objectives for the research in Chapter 1. The following section discusses the aims and objectives that were achieved in the research.

The problem that was addressed in this thesis can be summarised as follows:

Timber construction as an alternative to heavy materials has the potential to reduce the depletion of non-renewable resources and the life cycle energy of residential developments. While there has been some initial research in this area, no connection has been made between the misperceptions of both the supply and demand side of construction nor the opportunity for increased uptake of timber in the residential building sector. Heavy materials, in particular reinforced concrete, masonry and steel, currently dominate the residential construction market. Therefore the main aim of this research is to understand if increased timber use can provide sustainability benefits whilst maintaining or improving on the current performance of traditional materials in the areas of cost, time and quality.

Arising from the above, the objectives of the research were:

9.4.1 Identifying current homeowner perception of timber use in homes and units and the reason for their particular material selection

A preliminary literature review was undertaken followed by a survey questionnaire of Sydney homeowners. The questionnaire responses established the key issues for the reluctance of homeowners to use timber when building or renovating a home. These issues were mainly based on a homeowner's experience of design failures that resulted in insect damage, deterioration of timber due to weathering, and poor thermal performance related to insulation. Perceptions of fire, acoustic and maintenance problems were also identified as influential factors in the reluctance for timber selection over traditional materials.

Research literature identified that similar perceptions were held by home owners and occupants in Europe although recent research on the actual performance showed that many of these perceptions were either incorrect or had been rectified through scientific innovation in the design and installation of timber products in residential construction. Environmental sustainability, and aesthetics were listed as the main positive attributes of timber by survey participants. In identifying the perceptions of homeowners and occupants, further issues were raised regarding timber construction that included insurance, timber supply and construction quality.

9.4.2 Examining the benefits and barriers to the increased use of timber as an alternative to steel, masonry and concrete

This objective was achieved through analysing and undertaking interviews with construction practitioners from large and medium construction firms involved in Australia's residential sector. These interviews provided insights into the opportunities for and barriers to the increased use of timber in the types of developments in which they were participants. The whole spectrum of construction practitioners was included in order to gain perspectives from the design side, cost management, sustainability aspect, scheduling, site management and contractual administration. Barriers raised in interviews incorporated legislation, approvals and certification challenges. Insurance, maintenance and durability were discussed as issues more for the future owners than the construction process. Convincing the demand side to purchase timber residences was not seen as an issue. Challenges of fire and acoustic performance as identified in the survey were only considered a small hurdle. Having reliable costs, timber availability and skilled trades to install the products were considered most important by practitioners. Predicted benefits of timber use focused on the reduction in time of the construction process, increased safety, reduced site costs associated with lower numbers of site personnel and equipment, and the marketing opportunities related to sustainability. The other significant challenge was the barriers to entry for small and medium firms due to high costs of research and development and system development. The data collected from these interviews and the literature on construction project performance criteria were used investigate the current residential development model.

9.4.3 Identifying the current residential development model based on the traditional use of heavy materials

Seaden and Manseau (2001) explained the complexity of the construction industry and the numerous players affected by any change or innovation that occurred in building projects. Innovation in construction is slow and therefore takes a long time to be implemented and usually focuses on minor innovations in products or processes to increase efficiency. Nolan (2009) outlined the building procurement process in Australia and identified barriers to introducing timber to the current method of procurement. In order to identify the current value provided to clients through the building procurement process for heavy materials, the responses of 32 residential developers were examined and summarised into a model that focused primarily on the four main elements of construction performance. These elements have been identified firstly in project management literature and confirmed in interviews with construction practitioners. Cost, quality, time and sustainability – in that order of importance – were the basis of the value offered to clients. There was a lack of benefit to the client when it came to time and very minimal consideration of sustainability during the life cycle of the buildings offered. There was also a lack of consideration through this process of the end of life scenario for heavy materials. These shortfalls identified in the current model were used to assist in the development of a sustainable timber residential model.

9.4.4 Developing a sustainable timber residential development model

A key theme in the literature regarding the concepts of sustainability is the reduction or elimination of the use of finite resources and an increase in the use of renewables. The application of sustainability in the construction industry has focused on reducing the operating energy of buildings and, more recently, to the reduction of embodied energy in materials used. Project management literature has also emphasised the need to add sustainability to the critical success factors in projects, namely, time, cost and quality. The sustainable timber residential model was developed to achieve sustainability goals whilst not compromising the other project success factors. The model uses circular thinking in its application to construction by viewing material inputs from a life cycle perspective. This perspective incorporates the energy used to create, maintain, demolish, dispose or reuse the materials in residential development. It requires consideration of sustainability from the beginning of the project or design stage in order for efficient substitution of timber for heavy materials. This allows for an equitable comparison between the sustainable model and the traditional model.

9.4.5 Verifying and testing of the sustainable residential development model

Ten building case studies were undertaken to verify that the sustainable model provided benefits over the traditional model when tested. Life cycle cost and energy along with construction time were the variables of analysis based on comparable thermal performing timber and heavy material structures.

All ten case studies demonstrated that life cycle energy for the timber designs was lower than each of the traditional heavy material designs. All ten cases also showed quicker construction times for the timber design when compared to the traditional design. Seven of the ten case studies had life cycle costs less than for the traditional design. The case studies show that the sustainable timber residential development model can be applied to traditionally designed and constructed residences to achieve greater performance in sustainability, time and cost when designed for similar thermal performance. The cost performance, however, requires further research to investigate why the three timber redesign properties performed worse than the traditional designs.

9.5 Limitations with research and the sustainable residential development model

This research demonstrates that a sustainable residential development model applied to Australian homes reduces the construction time, life cycle cost and life cycle energy when compared to the traditional model using heavy materials. A number of limitations of this research have been recognised and these relate principally to the collection of data, case study scope and cost results.

Firstly, limitations of the survey questionnaire were the number of final responses. The response rate was lower than expected at only 15% and was pooled from NSW only. Interviews were procured with a wide range of construction professionals who provided a range of perspectives while access to construction practitioners that had worked on multi-residential timber structure was limited. This is due to there being only one company that had completed a large timber apartment building in Australia. One interview was conducted with the business manager of a company that did not allow access to design practitioners on the particular project. A lot of information was withheld regarding project costs and research and development, being protected company intellectual property. Interviews with more designers such as engineers and architects along with the project manager and service consultants would have provided greater insight into structural timber use in large residential buildings.

Another limitation of this research is the data results obtained from testing the sustainable residential development model on the building case studies. Only 70% of the life cycle cost results showed an advantage to the timber designs and, with just ten cases, there could be a variety of reasons for this result. The extensive data analysis process and time constraints prohibited additional numbers of cases to be conducted to identify the major contributors of the construction part of the LCC.

A scope limitation to the case studies is that they were sourced from NSW only. There are slight differences across the climate zones in Australia in the approach to construction and the materials dominating the construction process in each of the States. Case studies conducted in all the States could provide different results so future research could incorporate a wider scope of the case studies. Another scope limitation is that the cases used were based on relatively flat blocks with minimal slopes. Although it is anticipated that steeper blocks would provide further advantage to the timber model, a range of sites with different gradients would provide more comprehensive results.

The final limitation of the study can found in the circular sustainable model in the reuse and recycling part of the end of life stage. As there is no legal obligation for demolishers to reuse or recycle all the materials in residential buildings, there is limited literature or industry data on this part of the life cycle. It is also hard to predict the policies that will be in place at the end of the 50-year building life. This part of the sustainable residential model will need future evaluation as research develops in the area of construction waste, recycling and reuse and as tighter legislation is implemented reduce landfilling. The next section discusses the opportunity for further research.

9.6 Recommendations for further research

A review of the literature shows that this thesis is the first piece of research to look at the how the traditional model for residential development can be modified to create a more sustainable, cost effective and time effective model through the use of timber. It is also the first piece of literature to apply a circular approach to residential development using timber and to test it through multiple case studies. This research provides a good basis to build upon and there are future research possibilities to follow on from it. Section 9.5 discussed some limitations of the research and the sustainable residential development model and from these limitations various avenues for further research opportunities arise. The key areas for future research are outlined in the following sub-sections.

9.6.1 Undertake building case studies on multi-storey residential developments

As discussed in this thesis there is a lack of multi-storey timber residential buildings in Australia with only one recently completed ten-storey timber apartment block and a medium-rise residential project using timber cassettes, both in Melbourne. There are more cases in the UK and Europe, but these countries have different conditions for construction legislation as well as government and industry support for sustainable timber use in larger buildings. As the incidence of cases increases in Australia and information becomes available, more case studies could be conducted using the sustainable model developed in this thesis and applied to medium- and high-rise timber projects.

9.6.2 Broaden the scope of case studies using homes in different states and on different sites

As mentioned in Section 9.5, the thesis exposed some limitations related to the location and the gradients of the sites used in the case study. A number of different climate zones can be found in each State of Australia and different thermal performance is required in each zone (BCA 2013). Case study testing would be valuable to check if the extremes of temperature combined with the variable availability of local materials differ significantly from the ten cases used in this study. Another two variables that could be used to test the sustainable residential development model is the gradient of the site and the foundation material. Model testing was based on actual sites with M class soil (moderately active clay) and gradients <10%. Changes to the case study results are expected with steeper sites and variable foundation material. Steeper sites require more excavation and fill activities, increased footing beams and piers for the heavy material homes. Highly reactive clay or rock foundations will affect the concrete slab design in the heavy material cases and sandy soils will change the requirements for the timber footings. For these reasons, a larger case study incorporating a range of different soil conditions and site slopes would provide greater validity for the application of the sustainable residential development model.

9.6.3 Investigate prefabrication use to increase the life cycle benefits for timber homes implementing the sustainable development model

The case studies used in the testing of the sustainable residential development model implemented current construction processes for the timber cases when compared to the traditional heavy material cases. Some prefabrication is presently used in internal timber frames and timber roof trusses of the brick veneer cases. There is also prefabrication of timber roof trusses in the timber alternative although there is an opportunity for increased prefabrication in timber residential projects. A few companies are starting to test prefabricated ground and first level floor structures that reduce site labour, construction waste and construction time for detached dwellings. Other research has commenced on the reduction of heavy materials used in footings in detached timber dwellings. There is a further opportunity for research to be carried out with industry partners to test how the sustainable residential model will be improved with the use of increased prefabrication.

9.6.4 Test the sustainable residential development model on real life case studies

Chapter 8.6 tested how the use of timber could be used in residential housing projects to improve time, life cycle cost and life cycle energy compared to the traditional residential model. Further research remains to be done in this area, particularly in regard to implementing and testing the timber case study side by side with the traditional in an actual build. This would allow for real time and cost to be measured based on actual construction processes applicable to an identical design for both models and accommodating the same site conditions. Limitations to this proposal would be based on convincing a volume builder to adopt the SRDM and implement it in their development project. This would also add research and development costs to their business that developers may not wish to absorb. Another option is to have collaboration between research facilities and industry partners to assist funding such a proposal.

9.6.5 End of life scenario of residential building materials and designing for disassembly

Figure 7.4 in Chapter 7 shows the linear flows of heavy materials in the traditional building life cycle with recycling restricted to low grade construction products. Figure 7.5 provides an example of the circular flows that are possible using timber that can be reused in future projects if timber buildings are removed from site non-destructively. This would not only reduce the energy required for producing new materials but would also reduce the quantity of materials going to landfill. Further research could include working with the businesses involved in construction demolition and waste disposal to identify economical ways to disassemble and preserve materials for reuse and also to identify the barriers to greater levels of recycling and material reuse. Additional investigations could also look at how to design residential buildings for deconstruction and possible innovations in efficient assembly of building envelopes.

9.7 Conclusions

This thesis has successfully examined the issues around perceptions of the use of timber in residential building projects from both the demand side of housing (homeowners and occupants) and the supply side (developers, builders and construction practitioners). The study was undertaken to discover whether timber products could provide part of the solution to reducing Australia's construction industries' impact on the environment. The traditional method of residential construction utilizes heavy materials that are both non-renewable and are high in embodied energy when compared to timber. Survey questionnaires discovered that homeowners believe timber is a sustainable material yet they are reluctant to use timber due to incorrect or outdated perceptions of the performance of timber in residential properties. Interviews with construction professionals revealed that they are willing to use timber in new developments as a sustainable alternative to heavy materials if it can fulfil the other critical performance indicators in construction projects (cost, time, and quality).

A sustainable residential development model using timber was developed to address the issue of high energy use by heavy materials in the traditional model of residential development. A life cycle perspective was adopted in the sustainable model that considers the life cycle energy, life cycle cost and construction time. Building case studies were then used to test the model against the traditional model using heavy materials. Ten case studies using redesigned timber buildings with the same thermal performance and envelope dimensions as projects built from heavy materials were compared on a life cycle perspective. The timber design was clearly more efficient than the traditional buildings in construction time and life cycle energy and more efficient in life cycle costs. This research demonstrates that timber is a more sustainable option for Australian residential developments over the life of the building. Further cases applying the sustainable residential model to a wide range of locations and sites in the Australian volume building market are the next step in the theme of this research.

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Appendices

Appendix 1 Timber use in residential development

Table A1.1 Current uses of timber in Australian houses

Element	Typical timber used	Advantages/ Disadvantages	Frequent Use	Comment
Footings	Hardwood/treated pine stumps	Rotting and insect attack	No	Trad. use/ cost efficient for steep land.
Ground floor Structure	Kiln dried hardwood	Rotting/insect attack, dimension variations	Yes Reducing	Trad. Use for bearer and joist construction
	Treated MGP	Longevity/ simple fixings	Yes Reducing	Used in place of hardwood
	LVL	Straight/increase spans/cost efficient	Increasing	↑ Speed of construction
	I beam/I joist	Light/straight /cost efficient	Increasing	↑ Speed of construction
Floor coverings	Select Hardwood e.g. Vic ash, Blackbutt etc.	Expensive/durable/ Appealing	Yes	High-end construction.
	Cyprus Pine	Durable/expensive	Yes Reducing	Trad. Economical
	Veneers/floating floors	Cost efficient/ easy installation	Increasing	Used over existing floor
	Particleboard	Cheap/simple fixing	Yes	Usually carpeted
Wall structure	MGP	Cheap/availability/standard sizes & applications.	Yes	Most new homes will have MGP treated timber frames.
	Hardwood/ Oregan	Expensive	No	Used for renovations
Interior wall lining	Pine/Western Red Cedar/ Hardwood	Visually Attractive/ ↑Installation time	No	Trad. Use in Qld homes (hardwood)
First floor Structure	MGP	Cheap/dimensional imperfections	Yes Reducing	Main option prior to I beam & LVL
	I Beam	Light/cheap/ straight	Increasing	Good for cutting service openings
	LVL	Long span/straight	Increasing	Good when clear spans below
Wall bracing	Masonite	More expensive than ply.	Reducing	Trad. Timber frame bracing
	Plywood/ OS'Brace	Sturdy/cheap	Yes Increasing	Readily available

MGP-Machine graded pine **Trad. -Traditional**
Mod. Moderate use **LVL-Laminated Veneer Lumber**
OSB-Oriented strand board **KDHD-Kiln dried Hardwood**

Table A1.1 (continued) Current uses of timber in Australian houses

Element	Typical timber used	Advantages/ Disadvantages	Frequent Use	Comment
Exterior wall cladding	Composite hardwood	Pre-primed/easy installation/ some maintenance	Yes	Architectural design houses.
	Treated Pine H3	Cheap/ some maintenance/ warping	No	Alternative use to hardboards
	Western Red Cedar	Durable/expensive/high maintenance	No	Trad. Use with timber clad homes
	Hardwood	Expensive/ some maintenance/ durable	No	Architectural feature. Often allowed to grey
Roof structure	MGP stick built	Time consuming/ Non standard design	No	Good for renovations/↓ skill base.
	MGP truss	Quick/ cheap	Yes	Most new homes
	LVL	Longer spans/more expensive	Increasing	↑ use to create attic space
Roof covering	Timber Shingles	Very expensive	No	Heritage or one off designs
Ceiling lining	KDHW /pine feature	Expensive	No	Trad. Use in QLD homes. Feature in cathedral ceilings
Windows and doors	Western Red Cedar	Very Expensive/ light/ attractive	No	Architectural feature/ bi-folds
	Pine	Cheap/must be painted	Increasing (Doors)	Finger jointed and pre-primed
	Meranti, Tas. Oak	Attractive/durable	Yes	Often used for front doors & windows.
	KDHW	Expensive/heavy	Yes	Mainly used for front doors
Lintels	LVL	Straight/light	Yes	↑use versus KDHD
	KDHW K17	Heavy/expensive	Yes	↓ deflection
	MGP	Light/cheap	No	
	Glulam	Attractive	Reducing	Internal feature
Decking	Treated Pine	Cheap/easy installation	Yes	High usage prior to Merbau
	Merbau	Attractive/ high maintenance/ slow installation	Yes Increasing	Often sourced illegally from rainforests
	Hardwood	Rotting/high maintenance	Reducing	Trad. Use prior to treated pine

Source: Nolan 2009; Forsythe, 2007; UTAS 2007)

Table A1.2 Preferred material uses in housing over timber

Element	Alternative material	Advantages/ Disadvantages	Frequent Use	Comment
Footings	Reinforced concrete	Durable	Yes	Essential for brick veneer
	Brick piers/dwarf walls	Expensive and time consuming	No	Used for sloping blocks with suspended slabs
	Galvanized steel Piers	Easy to install/ expensive	No	Instead of brick piers for bearer and joists
Ground floor	Concrete slab on ground	Durable/costly/ thermal mass	Yes	Majority of new homes
Floor coverings	Carpet	Comfortable/ requires regular replacement	Yes	Traps dirt and dust/common for bedrooms
	Vinyl	Cheap/ easy installation	No	Alternative to tiles
	Exposed concrete	Expensive/durable	No	Architectural feature
	Tiles	Durable/	Yes	Wet areas
Wall structure External	Brick	Durable/low maintenance	Yes	Veneer or cavity
	Concrete	Expensive/slow	No	Architectural designs
	Block work	Expensive & slow	No	Requires finish to beautify
	Steel frame	Quick/pest resistance/cost efficient	Mod.	Collapses in fire/ challenge to alter services
Exterior wall cladding	Cement render	Expensive/requires paint finish	Yes	Attractive finish
	Vinyl cladding	Low maintenance/cheap appearance	No	Trad. Alternative to timber
	Fibrous cement sheeting	Require surface finish (render, paint)/easy installation	No	Used to match new renovations to brickwork
	Aluminium	Low maintenance/ factory finished/Durable	Yes	Trad alternative to timber cladding
Interior wall lining	Plasterboard	Cheap/easy installation	Yes	Most common application
First floor	Concrete	Expensive/good acoustic resistance/ slow installation	No	High end application
Roof structure	Steel	Light/easy installation	Mod.	Alternative to timber/specialty trade

Roof covering	Steel	Easy installation /affordable	Yes	Insulation details important
	Clay/concrete tiles	Easy installation /affordable	Yes	↑Concrete tiles versus clay
Ceiling lining	Plasterboard	Cheap/easy installation	Yes	Most common application
Lintels	Prestressed concrete	High strength in small sections/ Easy to render	Yes	↑use in brick walls
	Galvanised Lintels	Aesthetically intrusive/poor binding to brick	Yes	Trad use in brick walls.
Decking	Concrete	Durable/costly	No	On ground or part of floor slab
	Tiles on cement sheeting/slab	Attractive/ durable	Yes	Common alternative to timber
	Plastic lumber	Durable/uses recycled materials	No	Similar appearance to timber

Source: Nolan 2009; Forsythe, 2007; UTAS 2007)

Table A1.3 Overview of some environment assessment tools used in Australia

Assessment tool/ regulation	Area covered	Building type	Performance measure	Mandatory	Cost
Australian Building Greenhouse Rating (ABGR)	Australia	Commercial (Used for NABERS commercial)	Energy	No	Annual assessment $2000-3000
AccuRate	Australia	Residential	Thermal Embodied	No No-under trial	Software $795 Training $2070 Annual lic. $295
Building (BASIX) Sustainable Index	NSW	Residential	Energy and water	Yes	Certificate $50/house $25/alteration $80/2 attached. $120/3 units + $20/add unit
Green Star	Australia	-Office -Residential -Education -Retail -Office/interior -Healthcare -Industrial -Public build. -Communities -Custom	Whole building “ “ “ “ “ “ Fit out only Whole building “ “ These products are under development	No	Certificate $22K/ NLA<10000m2. $27.5K/ 10-30000m2. $33K/ 30000m2+ N/A N/A N/A
Nationwide House Energy Rating Software (NatHERS)	Australia	Residential	Thermal	No	Accredited software tools are AccuRate, BERS, FirstRate
Building Energy Rating Scheme (BERS)	Australia	Residential	Thermal	No	Software $660 Training $1760 Annual lic. $395
FirstRate 5	Victoria	Residential	Thermal	No	Software $550 Training $2000 Annual lic. $440
National Australian Building Environmental Rating Scheme (NABERS)	Australia	-Commercial -Commercial -Commercial -Homes -Hotels -Retail -Schools -Hospitals	Energy Water/Waste Indoor environ. Energy/water “ “ “ “ These products are under development	Yes No No No No No No No	$2-$3000/year Self or variable for private assessment “ “ “ “ N/A N/A
Kinesis CCAP Precinct	Local Govern. Areas (LGA)	Precinct/ New Development	Land use Transport Embodied CO2 Energy& Water Affordability	No	Variable
e-Tool	Australia	-Residential -Commercial -Developments -Communities -Government	Whole building plus Embodied energy and ongoing maintenance	No	Free online use. Assessments & Certifications >$500.

Appendix 6.1 Questionnaire Survey

Residential Timber Construction Survey Preview Only

Introduction

Ethics Approval No: 2012-232A

PARTICIPATION INFORMATION

I would like to invite you to participate in the attached Residential Timber Construction Survey. The survey seeks your individual opinions as a home/unit occupant in a residential area of NSW. Your perception regarding home and unit building materials is requested so it is not necessary that you own your own home or unit.This research will assist in understanding the deterrents to current and future homeowners using timber in new home construction and renovation projects. It will also collect some information on consumers attitudes towards large timber residential unit blocks. This project is currently being undertaken through the University of Technology Sydney and has been approved by the universities' human research ethics committee.

Please note that all survey responses will be treated as confidential and will not be disclosed to any parties beyond the researchers named below. The questionnaire should take 10-15 minutes to complete. It requires you to simply ‘click’ on buttons against the answers that best suit your views in addition to completing a few short answer questions.

Your participation in the survey is voluntary and may be withdrawn at any stage before submission. Some of the information you provide may be used as part of a PhD dissertation document and articles in academic journals. If you are interesting in receiving some of the final results of the research there is an opportunity to provide your contact details at the end of the survey.

If you have any questions, please contact me at or or Dr. Grace Ding at Grace.ding@uts.edu.au or 9514 8659.

Your contribution by participating in this survey is very much appreciated. I look forward to receiving your response.

Thank you.

Yours faithfully

Douglas Thomas
PhD student
School of the Built Environment
Faculty of Design, Architecture and Building
P.O Box 123
Ultimo NSW 2007, Australia

Section 1-Background Information

Please fill in the following information that best describes your current status.

1. Age group

- 18-24
- 25-29
- 30-39
- 40-49
- 50-59
- 60-64
- 65+

2. Gender

- Male
- Female

3. What is your profession/career?

- Architect
- Quantity Surveyor
- Construction (Builder)
- Construction (Project Manager)
- Engineer (Construction e.g structural design, hydraulic, mechanical, electrical)
- Engineer (Other)
- Law
- Building trade
- Academic
- Developer
- Property

Other:

4. In which Suburb do you reside?

5. Postcode

6. What type of material is the external wall of your current place of residence made of?

- Brick veneer
- Timber cladding
- Double brick
- Concrete

Other:

7. What is the approximate floor area of your home/unit?

If actual measurements are unavailable please use the following guidelines (Small 3 bedroom home 120-150m2, Average 3 bedroom home 151-180m2, Average 4 bedroom home 181-220m2)
(1 bedroom unit 50-60m2, 2 bedroom unit 70m2+, 3 bedroom unit 80m2+)

- <120m2 (home)
- 120-150m2 (home)
- 151-180m2 (home)
- 181-220m2 (home)
- >220m2 (home)
- 50-60m2 (1 bed unit)
- 70m2+(2 bed unit)
- 80m2+ (3 bed unit)

Other:

8. How many people living in your household?

- ○ 1
- ○ 2
- ○ 3
- ○ 4
- ○ 5
- ○ 6

Other: ______

9. How many of these are adults? (18+)

- ○ 1
- ○ 2
- ○ 3
- ○ 4

Other: ______

10. Do you own a home and/or unit? (Outright or mortgaged)

- ☐ Home
- ☐ Unit
- ☐ Neither

11. Are you currently living in your own home or unit?

- ○ Yes (home)
- ○ Yes (unit)
- ○ No

Other: ______

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Residential Timber Construction Survey Preview Only

Section 2-Sustainable building materials for homes

	Strongly Disagree	Disagree	Undecided/Neutral	Agree	Strongly Agree
	SD	D	U	A	SA
1. Our society should focus more effort on preserving our environment	○	○	○	○	○
2. Environmentally sustainable materials should be used to build new homes.	○	○	○	○	○
3. Timber is an environmentally sustainable building material.	○	○	○	○	○

4. Would you be willing to pay extra to use the most environmentally sustainable building materials in a new home building project?

- ○ Yes
- ○ No (If no please go to question 6)

5. What percentage above the purchase price of a new home building project (e.g. $300,000) would you be willing to pay to use the most environmentally sustainable external wall and structural floor material?

- ○ <1% (<$3000)
- ○ 1-2% ($3-$6000)
- ○ 3-5% ($9-$15,000)
- ○ 6-10% ($18-$30,000)
- ○ >10% (>$30,000)

Other: ________

The following questions refer to building additions to residential dwellings.

6. Would you be willing to pay extra to use the most environmentally sustainable building materials in a home extension project?

- ○ Yes
- ○ No (If no please go to next section)

7. What percentage above the cost of a renovation (e.g. $100,000) would you be willing to pay to use the most environmentally sustainable external wall and structural floor material?

- ○ <1% (<$1000)

- 1-2% ($1-$2000)
- 3-5% ($3-$5000)
- 6-10% ($6-$10,000)
- >10% (>$10,000)

Other:

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Residential Timber Construction Survey Preview Only

Section 3-Rising cost of heating and cooling in homes

Note: Approximately 40% of the average home energy consumption is from heating and cooling.

1. Please estimate the increase of your electrical bill over the last year.

- ○ 1%
- ○ 2-5%
- ○ 6-10%
- ○ 11-15%
- ○ 16-20%
- ○ >20%

Other: ____________

2. Please choose the general year round thermal comfort level of your current residence.

- ○ Very uncomfortable
- ○ Uncomfortable
- ○ Neutral
- ○ Comfortable
- ○ Very comfortable

3. In which months of the year is your current residence too hot?

- ☐ October
- ☐ November
- ☐ December
- ☐ January
- ☐ February
- ☐ March

Other: ____________

4. In which months of the year is your current residence too cold?

- ☐ April
- ☐ May
- ☐ June
- ☐ July
- ☐ August
- ☐ September

Other: ____________

5. Would you construct a new home out of materials with the greatest insulation properties to reduce the need for heating and cooling?

- ○ Yes
- ○ No

6. Please rank the following materials according to their thermal insulation capabilities

for [illegible] house walls (No 1 representing the best thermal insulation)

- [ ] Brick veneer
- [ ] Insulated timber cladding
- [ ] Double brick
- [ ] Aerated concrete (Hebel)

7. Please rank the following materials according to their thermal insulation capabilities for structural floors of homes (No 1 representing the best thermal insulation)

- [ ] Reinforced concrete
- [ ] Insulated timber bearers/joists
- [ ] Waffle pod(foam insulation)/Reinforced concrete
- [ ] Timber bearers and joists

8. Would you choose insulated timber external walls and floors if it provided greater insulation than a brick veneer home with a concrete floor in a new home building project?

- ○ Yes (Please go to question 10)
- ○ No

9. If No for question 8 (please explain)

10. Would you pay a higher price for a new home building project with insulated timber external walls and floor if it provided greater insulation than a brick veneer home with a concrete floor?

- ○ Yes
- ○ No (Please go to question 12)

11. What premium would you be willing to pay for an insulated timber floor/wall home over a brick veneer home with a concrete slab (% above purchase price)

- ○ 1%
- ○ 2%
- ○ 5%
- ○ 10%
- ○ 15%
- Other: ______

12. Would you prefer to live in a timber or brick house?

- ○ Timber house
- ○ Brick house

13. Please explain the reason for your choice.

[ ]

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Residential Timber Construction Survey Preview Only

Section 4-Timber house construction

The following six statements relate to the use of timber in the construction of homes. Please fill in the box that best represents the extent to which you either agree or disagree with each statement.

	Strongly Disagree	Disagree	Undecided/Neutral	Agree	Strongly Agree
1. Timber cladding is time consuming and costly to maintain.	SD ○	D ○	U ○	A ○	SA ○
2. Timber performance in the presence of fire is of concern to me.	SD ○	D ○	U ○	A ○	SA ○
3. Timber is an aesthetically pleasing building material and creates a comfortable living environment.	SD ○	D ○	U ○	A ○	SA ○
4. Timber homes are quicker to build than homes with concrete floors/brick external walls.	SD ○	D ○	U ○	A ○	SA ○
5. Timber homes have a higher resale value than homes with concrete floors/brick external walls.	SD ○	D ○	U ○	A ○	SA ○
6. Timber homes are more expensive to build than homes with concrete floors/brick external walls.	SD ○	D ○	U ○	A ○	SA ○

7. The following features of timber would encourage me to use timber if I were building a new home or making alterations to an existing home. (1-most important, 6 least important)

- [ ] Renewable/sustainable building material
- [ ] Thermal performance
- [ ] Construction speed
- [ ] Cost
- [ ] Resale value
- [ ] Aesthetics

8. The following features of timber would discourage me to use timber if I were building a new home or making alterations to an existing home. (1-most important, 7

least important)

- [ ] Structural performance
- [ ] Building cost
- [ ] Thermal performance
- [ ] Maintenance time/cost
- [ ] Resale value
- [ ] Fire risk
- [ ] Durability (termites/water damage)

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Residential Timber Construction Survey Preview Only

Section 5-Multistorey residential timber units

There are a handful of 8-10 storey residential unit blocks internationlly which have floor and wall structures composed mainly of solid timber panels. The largest in the world will be 10 storeys high and is currently under construction in the Docklands area in Melbourne Australia. The final questions below ask your opinion surrounding the purchase/residing in a unit in one of these innovative timber structures.

1. Would you prefer to live in a ten storey structural timber or concrete building?

- ○ Timber
- ○ Concrete

2. Please choose two benefits in living in a tall timber unit building.

- ☐ Inexpensive
- ☐ Indoor air quality
- ☐ Aesthetics (if interior panels exposed)
- ☐ Beneficial for the environment
- ☐ Sound insulation
- ☐ Structural capacity

Other: __________

3. Please pick the two main concerns you would have if you were required to live in a tall timber unit building.

- ☐ Expensive
- ☐ Fire
- ☐ Structural capacity
- ☐ Water damage
- ☐ Insect attack
- ☐ Sound insulation

Other: __________

4. If you were buying a unit in a 10 storey residential apartment block, would you choose a structure made of timber or concrete?

- ○ Timber
- ○ Concrete

5. Please explain the reason for your choice in question 4.

6. Would you expect to pay more for the apartment in the timber or concrete building?

- ○ Concrete

- Timber
- They should cost the same.

7. How much more would you expect to pay?

- Zero
- $5000
- $10000
- $15000
- $20000
- $25000
- $30000

Other:

Further Information

If you would like a summary of these survey results please provide a contact email so that they may be provided once correlation is complete.

If you are working in the construction industry and would like to participate in a short face to face interview regarding the use of structural engineered timber in medium/high rise residential unit blocks please provide some contact details e.g name/phone/email.

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Appendix 6.2 Questionnaire participants-LGA

Table A6.1 Questionnaire participants by Local Government Area (LGA).

REGION	LOCAL GOVERNMENT AREA (LGA)	No.	TOTAL
Inner Sydney	Manly	8	
	Willoughby	10	
	North Sydney	6	
	Mosman	8	
	Lane Cove	3	
	Hunters Hill	3	
	Canada Bay	10	
	Leichardt	10	
	City of Sydney	20	
	Woollahra	2	**144**
	Waverley	5	
	Ashfield	6	
	Burwood	0	
	Strathfield	5	
	Marrickville	23	
	Canterbury	7	
	Botany Bay	3	
	Randwick	8	
	Rockdale	4	
	Kogarah	0	
	Hurstville	3	
Outer Sydney	Pittwater	4	
	Hornsby	13	
	Warringah	9	
	Karingal	12	
	Ryde	12	
	The Hills	6	
	Parramatta	4	
	Holroyd	1	**99**
	Blacktown	4	
	Auburn	4	
	Bankstown	3	
	Penrith	3	
	Fairfield	1	
	Liverpool	3	
	Camden	0	
	Campbelltown	2	
	Sutherland	18	
Sydney Surrounds	Wyong	1	
	Gosford	0	
	Hawkesbury	1	**4**
	Blue Mountains	2	
	Wollondilly	0	
Illawarra	All LGA's	8	**8**
Other regions	All LGA's	5	**29**
Not provided	Not applicable	11	**13**

Appendix 6.3 Questions for Semi-structured interviews with Construction professionals

Specific to companies planning/building a multi-storey timber building

How has your company overcome the building codes issues related to fire protection and acoustic ratings of the floors/walls?

Has a comparative cost analysis been carried out between Cross Laminated Timber and reinforced concrete for the project? If so, how did timber compare?

How did you choose your design team consultants (Considering the limited experience in Australia)

What challenges did you come across in the planning and design stage of the timber project?

What are the plans for storage of Cross Laminated Timber panels once in Australia? (? On-site/ warehouse close to the site).

Who would install Cross Laminated Timber panels? (e.g. experienced carpenters/riggers or specialist team from Europe)

Specific to project/construction managers

Have you heard of the intention by some construction companies/ architectural firms to design and build structural timber residential buildings over 8 storeys.

Do you see CLT timber buildings as a feasible long-term option for sustainable residential unit buildings or more suited for isolated projects with environmental marketing benefits?

Would you feel confident in managing a timber building 4-10 storeys high relying on timber elements for the main structural support?

What do you believe are the advantages to using mass timber in medium rise construction?

What do you believe are the disadvantages to using mass timber?

What are some of the barriers to introducing a new construction technology such as medium rise timber buildings into the construction industry?

Who should install Cross Laminated Timber panels? (E.g. experienced carpenters/riggers or specialist team from Europe)

Specific to designers of multi-storey timber buildings

Would you feel confident designing one of these buildings?

How would you overcome issues with fire and acoustic protection of solid timber elements during construction and at the completion of the project?

What sort of durability issues can you foresee with the use of timber as the main construction element in a large unit block?

What are some of the particular advantages and disadvantages associated with designing mass timber elements in a multi-storey timber building?

At what stage should education about this type of innovative construction method be introduced into construction professionals' undergraduate course**?**

Which stages during the approval process do you see as the most challenging to overcome?

Appendix 8.1 Thermally adjusted LCE for thermal rating discrepancies

Project No.	Thermal Star rating		LCE MJ 50yrs		LCE MJ 50yrs-Adjusted for thermal rating difference		GFA m2
	Brick	**TImber**	**Brick**	**Timber**	**Brick**	**Timber**	
1	5.9	5.6	2230506	2009116	2230506	2093486	286
2	5.8	6.0	3051217	2827443	3190653	2827443	286
3	5.4	5.0	1900948	1708336	1900948	1840006	171
4	4.9	6.2	2471915	2234080	2718194	2234079	262
5	5.6	5.5	1947019	1760811	1947018	1774251	192
6	5.2	5.4	2475470	2221483	2574470	2221482	264
7	6.1	6.1	2476941	2274446	2476940	2274445	260
8	4.7	4.2	1851943	1696303	1851942	1836523	171
9	6.2	6.1	2122896	1943651	2122895	1953251	240
10	4.9	5.4	1144086	1037806	1424885	1037805	130

Appendix 8.2 Cost of LLC energy difference between timber and brick associated with different star rating

Brick pilot case power calculation		
Total annual MJ		
Gas	**55433**	
Electricity	**34324**	
	Calculations	
		KWh=0.27777
Daily Gas	152	
Daily electricity	94	26.12103419
Typical gas	**21760**	
Hot water	18481	
Cooking	3279	
Heating gas	**33673**	AccuRate data
Total	55433	
Typical electricity	**33048**	
Refrigeration	9393	
Lighting	4662	
Dishwasher	2674	
Washing machine	1920	
Dryer	1234	
Entertainment	6514	
Computing	1988	
Other	4662	
Cooling electricity	1276	AccuRate data
Total	34324	

Timber pilot case power calculation			
Total annual MJ			
Gas	**52645**		
Electricity	**35059**		
	Calculations		
	MJ=1	KWh=0.27777	
Daily Gas	144		
Daily electricity	96		26.67365562
Typical gas	**21760**		
Hot water	18481		
Cooking	3279		
Heating gas	**30885**	AccuRate	
Total	52645		
Typical electricity	**33048**		
Refrigeration	9393		
Lighting	4662		
Dishwasher	2674		
Washing machine	1920		
Dryer	1234		
Entertainment	6514		
Computing	1988		
Other	4662		
Cooling electricity	2011	AccuRate	
Total	35059		

Brick house	
Total annual power $	**4508**

Annual Electricity $		**2748**
	Calculations	
Electricity	AGL 2/11/14	
Supply per day	78.12c/day	
	Dollars	
Quarter supply		71.2845
Quarter KWh		2383.54437
First 1750kWh	25.01/kWh	
First 1750kWh		437.675
Remaining kwh	28.12c/kWh	
Remaining kwh		178.1526768
Electricity/ quarter		687.1121768

Annual GAS $		**1760**
	Calculations	
Supply per day	AGL 2/11/14	
Daily supply	56.76c/day	
Quarter supply $		51.7935
Quarter MJ		13858.25
First 3750 MJ in cents	4.0964c/MJ	
Next 4499 MJ	2.3452c/MJ	
Next 17249MJ	2.3012c/MJ	
Calculation $		
First 3750 MJ in cents		153.615
Next 4499 MJ		105.510548
Next 17249MJ		129.074308
Gas/Quarter		439.993356

Timber house	
Total annual power $	**4501**

Annual Electricity $		**2805**
	Calculations	
Electricity	AGL 2/11/14	
Supply per day	78.12c/day	
	Dollars	
Quarter supply		71.2845
Quarter KWh		2433.971075
First 1750kWh	25.01/kWh	
First 1750kWh		437.675
Remaining kwh	28.12c/kWh	
Remaining kwh		192.3326663
Electricity/ quarter		701.2921663

Annual GAS $		**1696**
	Calculations	
Supply per day	AGL 2/11/14	
Daily supply	56.76c/day	
Quarter supply $		51.7935
Quarter MJ		13161.25
First 3750 MJ in cents	4.0964c/MJ	
Next 4499 MJ	2.3452c/MJ	
Next 17249MJ	2.3012c/MJ	
Calculation $		
First 3750 MJ in cents		153.615
Next 4499 MJ		105.510548
Next 17249MJ		113.034944
Gas/Quarter		423.953992

Operating cost LCC-affect of thermal rating between timber and brick

Operating cost LCC-	Heating/cooling/appliances/hot water/lighting

	Discount rate 5%	Annual cost brick	Annual cost timber
Years	Factor		
1	0.9529	4296	4289
2	0.907	4089	4082
3	0.8638	3894	3888
4	0.8227	3709	3703
5	0.7835	3532	3527
6	0.7462	3364	3359
7	0.7107	3204	3199
8	0.6768	3051	3046
9	0.6446	2906	2901
10	0.6139	2767	2763
11	0.5849	2637	2633
12	0.5568	2510	2506
13	0.5303	2391	2387
14	0.5051	2277	2273
15	0.481	2168	2165
16	0.4581	2065	2062
17	0.4363	1967	1964
18	0.4155	1873	1870
19	0.3957	1784	1781
20	0.3769	1699	1696
21	0.3589	1618	1615
22	0.3418	1541	1538
23	0.3256	1468	1466
24	0.3101	1398	1396
25	0.2953	1331	1329
26	0.2812	1268	1266
27	0.2678	1207	1205
28	0.2551	1150	1148
29	0.2429	1095	1093
30	0.233	1050	1049
31	0.2204	994	992
32	0.2099	946	945
33	0.1999	901	900
34	0.1904	858	857
35	0.1813	817	816
36	0.1727	779	777
37	0.1644	741	740
38	0.1566	706	705
39	0.1491	672	671
40	0.1421	641	640
41	0.1353	610	609
42	0.1288	581	580
43	0.1277	576	575
44	0.1169	527	526
45	0.1113	502	501
46	0.106	478	477
47	0.1099	495	495
48	0.0961	433	433
49	0.0916	413	412
50	0.0872	393	392
Total for 50yrs		82370	82242
		Difference over 50yrs/%	0.0015

THE END