The application of structural contingency theory to supply chain management – developing a strategic model for prefabricated timber systems

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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.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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Conference papers

- Holmes, M., Crews, K. & Ding, G. 2011, 'The influence building codes and fire regulations have on multi-storey timber construction in Australia ', paper presented to the *World Sustainable Building Conference* Helsinki, Finland
- Holmes, M., Crews, K. & Ding, G. 2012, 'Supply Chain Management Strategies for Engineered-to-Order timber structural systems'. Paper presented to the RIC COBRA Conference, Las Vegas, Nevada, USA

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- New innovative prefabricated timber systems for multi-storey construction presentation for EG Property Group – Lunch and Learn session, August 2012, Sydney, Australia
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- Smith, T., Holmes, M. & Carradine, D. 2012, *A Full Construction, Deconstruction and Reconstruction cycle Cost and Construction analysis of the STIC test building*, Structural Timber Innovation Company (STIC), Christchurch, New Zealand

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- Holmes, M., Crews, K & Ding, G., 2012 Supply Chain Management strategies for prefabricated timber systems in multi-storey non-residential construction, presented to World Conference Timber Engineering (WCTE) 2012, Auckland, New Zealand

Abstract

There is currently limited market penetration for prefabricated timber structural systems in non-residential multi-storey construction in Australia and New Zealand. This limited penetration is caused in part by a fragmented supply chain. There is a need for manufacturers, fabricators and designers to align themselves to better meet the needs and expectations of the non-residential construction environment. There is limited literature available on the impact of the supply chain on other Engineered-To-Order (ETO) products and there is a gap in knowledge on how the supply chain impacts on the performance of prefabricated timber systems. The manufacturer in the prefabricated timber supply chain is the key figure preventing the entire supply chain being structured to better meet the needs of the end user. The prefabricated timber construction supply chain is not structured with the end user in mind, thus decreasing its value. The prefabricated timber supply chain in its entirety should be structured for the non-residential market to better suit the needs of the customer rather than the supplier. Structural contingency theory outlines there should be a fit between the organisational processes and the environment. It states that company models that match the environmental requirements should perform more successfully than those that do not. When applying structural contingency theory to the supply chain the individual dimensions of supply chain should be aligned in order to achieve the best performance.

Case studies interviews were undertaken with industry practitioners and senior leaders from organisations along the supply chain for prefabricated timber systems in Australia, New Zealand (NZ), United Kingdom (UK), Austria, Germany and Finland. These were undertaken to establish how and why the supply chain and organisations along it impact on the performance of prefabricated timber systems. These interviews together with current state-or-art of literature formed the basis of the preliminary supply chain model. Building case studies were then undertaken to further clarify these issues and test structural contingency theory, with the supply chain as the environment, the theory was tested using prefabricated timber systems.

Chapter 1 Introduction

This thesis studies how the organisations along the supply chain impact on the time, cost and quality of prefabricated timber systems in the construction industry. While previous research has recognised the potential for prefabricated timber systems to compete with concrete and steel in the non-residential construction market, less is known about how the supply chain impacts on their commercial viability. This thesis considers supply chain management (SCM) as a means of addressing the problem. The study draws heavily on concepts from SCM with a specific focus on strategic procurement and its application to structural contingency theory.

1.1 Background

The construction industry is renowned for its fragmentation together with its lack of research and development into innovative products and systems. There is a general inertia to change from traditional forms of construction and adopt innovations. The construction industry has an extensive influence on economies and the environment – where buildings in developed countries account for 20-40% of energy consumption (Lombard, Ortiz & Pout 2008). The Australian Bureau of Statistics (2010) highlighted the construction industry was responsible for 7.0% of GDP in 2007-08 and 6.8% in 2008-09. The construction industry as a whole has been blamed for lagging behind other industries with respect to productivity improvement, cost reduction, and project duration. Prefabrication is one way to help improve productivity in the industry (Gosling & Naim 2009). In particular prefabricated timber systems are lightweight, quick to erect and environmentally sustainable. The environmental properties of materials are not traditionally a design or construction priority, with performance characteristics (time, cost and quality) typically governing the choice of structural materials (John et al. 2009). This tendency is changing as the issues associated with climate change continue to come to the forefront and governments and industry look for ways to assuage its effects. Choosing environmentally sustainable building materials is beginning to become a client and tenant expectation and industry is starting to follow suit. One way of measuring environmental performance of materials is through Life Cycle Assessment (LCA) studies, which have argued when timber is used as an alternative structural material to steel and concrete the overall environmental impact of the building can be reduced (John et al. 2011; Page 2006; Perez 2008).

Innovations help the construction industry increase productivity and in order for new products to become viable and adoptable en masse into the construction industry they need to meet a number of key performance requirements – namely time, cost and quality. SCM has the potential to improve time, cost and quality as it views the entire supply chain instead of individual parts or processes (Christopher 2011). This helps improve transparency and alignment of the supply chains' coordination (Vrijhoef & Koskela 2000). Tommelein, Walsh & Hershauer (2004) argued SCM as the leading process improvement, cost saving, and revenue-enhancing business strategy practiced in today's business world. SCM can be applied to products, companies and projects and has a number of different perspectives including distribution, production, strategic procurement and industrial organization economics. The way SCM can be implemented also varies depending on the type of products i.e. Make To Stock (MTS), Assemble To Order (ATO), Make To Order (MTO) and Engineered To Order (ETO). Prefabricated timber systems are an ETO product, which have a unique supply chain in that the decoupling point is located at the design stage, where each product undergoes a detailed design process. This makes the adoption of SCM in ETO products inherently more difficult than other products due to the increased complexity and processes involved in the supply chains.

1.2 Problem definition

The limited literature available on the impact of the supply chain on ETO products is matched by a gap in knowledge on how the supply chain impacts on the performance of prefabricated timber systems. In Australia and New Zealand (NZ) prefabricated timber systems have seen little use in the non-residential construction market, with concrete and steel primarily being used for structural elements. With the advent of a price on carbon imminent, sustainable material options will become increasingly important. As there has been limited demand for prefabricated timber systems in Australia and NZ, the supply chain for such systems is limited in capacity.

The current supply chain presents a barrier to the use of prefabricated timber systems and is something that needs to be looked at in greater detail. 'The gap in the supply of the system [prefabricated timber] must be addressed in order for the method of construction to become truly viable' (Smith 2008 p. 117). The gap in the supply side is caused in part by a gap in the demand side, which has in turn prevented necessary investment.

Structural systems in buildings constitute a large proportion of costs (Table 4-4) and ensuring these systems can be delivered to a pre-determined cost, time and, to a certain degree, quality, is of critical importance to the project overall. With the advent of innovative prefabricated timber systems such as EXPAN and Cross Laminated Timber (CLT) into the Australian and NZ markets, there is now an opportunity for timber to be used in multi-storey non-residential buildings. Currently there is limited industry capability to produce and deliver these systems cost and time effectively in this commercial market.

Prefabricated timber systems are currently used predominantly in the residential market, which is a different environment to the non-residential market. The needs and expectations of clients are substantially different between the two markets. Most organisations involved in the production of prefabricated timber systems are currently geared towards the needs and expectations of the low-rise residential market. These organisations are performing poorly in the non-residential market, as their business models aren't set up in such a way that meets the needs and expectations of the environment. Following on from this structural contingency theory indicates there should be a fit between the organisational processes and the environment (Burns & Stalker 1961; Lawrence & Lorsch 1967). Structural contingency theory posits that company structures that match the environmental requirements should perform more successfully than those that do not and predicts under-performing companies will adopt a new business model that better fits the environment.

When applying this theory to supply chains the supply chain as a whole should be structured to suit the environment (Flynn, Huo & Zhao 2010). When applied to organisations involved in the production and delivery of prefabricated timber systems in Australia and NZ, structural contingency theory proposes these companies should change their structures to suit the non-residential environment. This will allow them to better meet the needs and expectations of customers in this market, and increase performance.

1.3 The application of structural contingency theory to supply chain management of prefabricated timber systems

SCM views the entire supply chain instead of individual parts - this helps improve transparency and alignment of the supply chains' coordination (Vrijhoef & Koskela 2000). A number of authors (Khalfan et al. 2008; Love, Irani & Edwards 2004; Saad, Jones & James 2002; Vrijhoef & de Ridder 2007; Vrijhoef & Koskela 2000) have outlined the benefits of an integrated supply chain and of incorporating SCM into the construction industry. Structural contingency theory outlines how organisational processes should be structured to suit the environment in which they operate (Burns & Stalker 1961; Lawrence & Lorsch 1967). Configurations that match the environment will perform better than those that don't and will help an organization achieve top performance. When applying structural contingency theory to SCM, individual parts of the supply chain should be aligned and organized in such a way that achieves the best performance. A group of individual companies can be formed to make the supply chain an extension of the organisation, and structured in such a way to suit a particular environment. If an ideal model can be established for the group of companies there is potential to improve performance of the entire supply chain. Applying supply chain integration and structural contingency theory to the problem: in order for prefabricated timber systems to be effective in the non-residential market the organisations along the supply chain need to be organised in a way that best ‘fits’ the clients’ needs and expectations in the environment.

1.4 Motivation for undertaking research

I have an interest in innovations, in particular, in seeing new products and processes adopted that improve buildings and our society as a whole. Throughout Europe prefabricated timber systems have proved to be a viable structural alternative to steel and concrete. Due to its lightweight and prefabricated nature, timber has demonstrated it can increase the speed of construction, improve cost outcomes e.g. reduced foundations and provide a safer working environment. Low noise and minimal waste during construction also make timber a convenient material for use in urban centres. Timber offers strong sustainability credentials due to its unique ability to sequester and store carbon. With carbon accounting imminent, low embodied carbon buildings and the use of timber beyond finishing trades in the multi-storey construction sector has wide benefits. This research was undertaken to establish what the key issues are along the supply chain preventing the viability of prefabricated timber systems, and to determine how applying structural contingency theory to SCM can improve the supply chain of prefabricated timber systems.

1.5 The Research Aims and Objectives

The previous discussion identifies a problem that hasn’t be addressed to date in literature. It can be summarised as follows:

Prefabricated timber systems have the potential to increase productivity in the non-residential construction market and provide a sustainable alternative to traditional forms of construction. While there has been some initial research, further work is required. It is important to understand how the supply chain impacts on the viability of these systems and what can be done to improve the performance of these systems. Arising from the above, the aim of the research is to develop a strategic supply chain model and to apply and test structural contingency theory in relation to ETO products – specifically prefabricated timber systems. Developing a theoretical understanding of the role of SCM as a tool to improve the performance of these systems will enable industry to better understand how the supply chain impacts on the performance of ETO products. This will also establish how SCM can be used to increase performance of these products, specifically relating to time, cost and quality.

The aims of the research are:

- To use SCM literature and structural contingency theory to develop a strategic model to improve performance of prefabricated timber systems in Australia and NZ, and
- To undertake empirical research (case studies) to empirically test the model and structural contingency theory in relation to prefabricated timber elements.

The objectives of the research are:

- To undertake a literature review to identify the current state-of-the-art of prefabricated timber in the construction industry and its potential as an alternative to traditional concrete and steel construction in multi-storey non-residential construction.
- To undertake exploratory case study interviews with industry professional to establish 'how' and 'why' the supply chain impacts on the performance of prefabricated timber systems in Australia, NZ and countries in Europe.
- To undertake research on 'how' the organisations along the supply chain impact on the performance of prefabricated timber systems and to examine 'why' organisations and the supply chain are structured or set up in a certain ways in Australia, NZ and Europe.
- To utilise SCM concepts as a framework for investigating the supply chain of prefabricated timber systems.
- To develop a strategic model aiming at addressing the time, cost and quality issues along the supply chain for prefabricated timber systems.

- To test the effectiveness and usefulness of the model on a building case study – to examine how it can improve time, cost and quality over the current supply chain model.

1.6 Research Scope and Focus

This research focus is on the supply chain for prefabricated timber systems used in structural applications. Prefabricated timber systems can be used for a number of non-structural applications in the non-residential market e.g. partitions and workstations. The research has a particular focus on Australia and NZ - though a number of European countries were also examined. In Europe prefabricated timber systems are a mature market; they have been used in multi-story non-residential and residential construction for the past few decades. Researching the European market was done to learn from European experiences and to provide a cross case analysis between the different regions.

Being an ETO product, prefabricated timber systems inherently have a more complex supply chain than other products i.e. consumer goods. This is due to the fact the decoupling point occurs at the design stage – where each system goes through the design stage and a unique solution is designed depending on project requirements. Figure 1.1 depicts a typical supply chain for prefabricated timber systems. The scope of this research is limited to the highlighted orange section of the supply chain. The research delves into the organisations involved, their processes, and the key issues that occur over these stages, that influence the time, cost and quality of the systems.

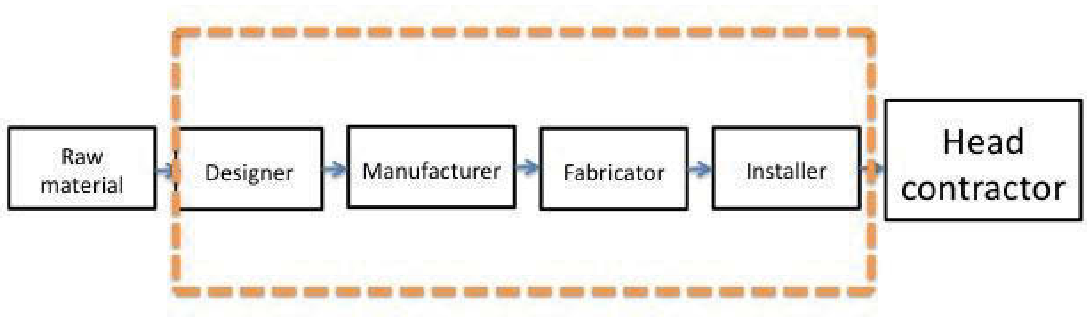

Figure 1.1 Prefabricated timber system supply chain and scope of research

Upstream from the design and manufacturing stages in the supply chain is raw material acquisition (logs) and in some cases sawmilling – depending on the prefabricated timber system. These stages (log supply and sawmilling) are out of the scope of this research. This decision was made because different logs are used for a number of different products i.e. pulp and paper, structural sawn timber, non-structural applications such as weatherboards, and so on, and the resulting upstream supply chain is different for each. It is an important stage that can affect time and cost of prefabricated timber systems and the organisations involved are focused towards supplying commodity products with little regard to move further upstream and value add the product. There is still value covering these areas and the issues relevant to this stage will be dealt with in the literature review in Chapter 4.

1.7 Research Method

The primary aim of this thesis is to develop a strategic model and to test the validity of structural contingency theory. In order to achieve these aims the research primarily uses 'how' and 'why' type questions in data collection. The study objective is focused on the supply chain of prefabricated timber systems - in particular new and innovative systems such as EXPAN, a new post-tensioned timber technology. EXPAN has only been used in the past couple of years in Australia and NZ and as a result is contemporary in nature. Case studies were used as the primary research method relying on Yin's (2009 pg. 13) argument that a case study is an empirical inquiry that investigates a contemporary phenomenon within its real-life context and accepting that you would use a case study method because you deliberately wanted to cover contextual conditions – being that they might be highly pertinent to your phenomenon of study.

The research has been undertaken in two parts. The first part consisted of case study interviews on the supply chain of prefabricated timber systems in Australia and NZ, Austria, Germany, UK and Finland. Case studies in each region were undertaken in two rounds. The first round focused on establishing the key time, cost and quality issues. The second round focused on 'how' the organisations were structured and the particular services they offered and 'why' they were set up in this way. Interviews were the prime data collection method in this first part. The data from these case studies was collected and analysed and results from these interviews helped to establish the supply chain model in Chapter 7. This supply chain model was developed to address the time, cost and quality issues outlined in the interviews. Strategic procurement SCM literature and structural contingency theory were also used to develop and support the model development.

The second part of the research involved three case studies, two actual building case studies in NZ and one set of prefabricated timber systems used for testing in Australia. These three case studies used EXPAN systems and the aim of these case studies was to empirically test structural contingency theory when applied to prefabricated timber elements. The hypothesis is organisations involved in the production and delivery of prefabricated timber systems needs to change their structures to suit the non-residential environment and better meet the needs and expectations of customers in this market to improve the performance in relation to time, cost and quality.

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. While previous research has recognised the potential for prefabricated timber systems to compete with concrete and steel in the non-residential construction market, less is known about how the supply chain impacts on the commercial viability of those systems. The current supply chain presents a barrier to the use of prefabricated timber systems and is something that needs to be looked at in greater detail.

Literature review

Chapter 2 reviews the literature on organisational theories, including classical management, scientific management and then contingency theory and how it developed into structural contingency theory. Structural contingency theory posits there should be a fit between the organisational processes and the environment.

Chapter 3 reviews and critiques the literature surrounding key themes in SCM namely, production, distribution, strategic procurement and industrial organization economics. From these key themes strategic procurement is highlighted to be the most relevant to this thesis – as strategic procurement incorporates strategies such as supply chain integration. Concepts such as strategic alliances, partnering and vertical integration are addressed in detail.

Chapter 4 reviews and analyses the literature on engineered wood products (EWPs) and prefabricated timber construction. The Australian and New Zealand (NZ) construction markets are of particular focus and a number of areas are addressed including: available key prefabricated timber systems, size and structure of the different construction markets, and issues preventing their use in non-residential construction.

Research method

Chapter 5 covers the methodology selected as the best fit for achieving my research goals. The research methodology used in this thesis is predominantly qualitative in nature. This chapter outlines the selection and application of the case study methodology and why it is the most applicable to this research. This chapter will address the various forms of data collection and data analysis methods.

Data collection

Chapter 6 presents the findings from part one of the research. Case studies were undertaken to find out key issues along the supply chain that affect the performance (time, cost and quality) of prefabricated timber systems. Interviews were the primary data collection tool, and were conducted with practitioners involved in the various stages of the supply chain for prefabricated timber systems.

Data analysis and model development

Chapter 7 analyses interview findings and then merges concepts of supply chain management and structural contingency theory into a conceptual model – the SBE model. A deductive research method using structural contingency theory is adopted to help develop the supply chain model.

Theory testing – building case studies

Chapter 8 presents the findings from three building case studies – two in NZ and one in Australia. These case studies were used to test the structural contingency theory in relation to the supply chain for prefabricated timber systems.

Data analysis and model validation

Chapter 9 analyses case the study's findings and validates and demonstrates the benefits of the SBE model through the use of a hypothetical building case study. It also outlines how the SBE model developed in Chapter 7 can be used to improve the performance (time, cost and quality) along the supply chain for prefabricated timber structural systems. It then examines how the SBE model is modified to incorporate findings from the building case studies and, finally, how (once adopted) it can help improve the performance (time, cost and quality) of prefabricated timber systems.

Conclusion and recommendations for future research

Chapter 10 provides an overall summary and conclusion chapter which covers a number of key areas, including firstly a brief summary of the research, a review of the aims and objectives, limitations of the research and finally recommendations for further research.

References

Appendices

Chapter 2 Structural Contingency Theory & Supply Chain Management

2.1 Introduction

This chapter provides a background on organisational theories, including classical management, scientific management and then contingency theory and how it developed into structural contingency theory. According to structural contingency theory, there should be a fit between the organisational processes and the environment. It advocates that company models (configurations) that match the environmental requirements should perform more successfully than those that don't (Burns & Stalker 1961; Lawrence & Lorsch 1967). When applying structural contingency theory to the supply chain, the individual dimensions of the supply chain ought to be aligned in order to achieve the best performance (Flynn, Huo & Zhao 2010).

This means the entire supply chains or business network should be structured in such a way as to achieve an ideal fit to best suit the external environment. Viewing the supply chain from a strategic perspective led to revolutionary changes, where supply chains began rethinking their organisational structure to suit the environment (Christopher 2011). In order to meet ever changing market demands, organisations have restructured to form a 'network', where the supply chain is an extension of the organisation (Christopher 2011; London 2004). This chapter reviews the literature that has applied structural contingency theory and organisational theory to SCM.

2.2 Organisational theories – background

Organisations play an important role in our economies where they are a provider of goods and services and employment. Over time the knowledge of organisations has progressed substantially. Robbins & Barnwell (2007) describe an organisation as a coordinated social entity with an identifiable boundary – within this boundary an organisation strives to make a profit and achieve long-term survival. Long-term survival can be obtained through decision-making and achieving management objectives. Achieving these objectives requires internal coordination within the organisation. In order to meet these objectives not only does an organisation need to manage its internal demands, it needs to coordinate interaction with its external environment. Porter's value chain concept outlines internal activities that an organization needs to manage, including primary and support activities as shown in Figure 2.1 (Porter 1985). These internal activities constitute the boundary of the organisation and outside this boundary the organization interacts with the external environment.

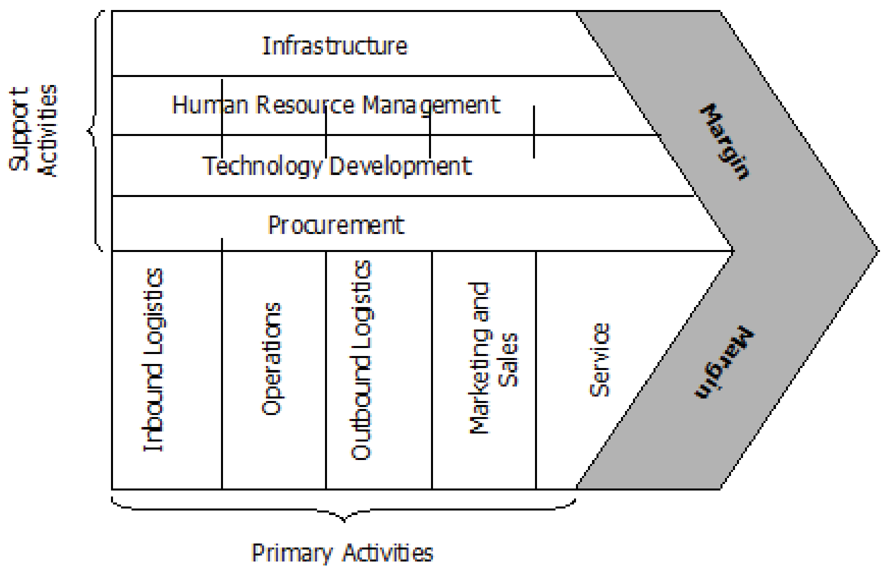

Figure 2.1 Porter's value chain

Source: Porter 1985

The management field consists of a variety of theories, schools and directions. Figure 2.2 provides an overview of the different schools of management. Since the turn of the 20th century the classical management school has been seen as the dominant school of thought. In the 1920s the human-oriented school was established with a focus on informal organizational structure, participative leadership and self-control. The decision theory school was then established in 1950 and consisted of various quantitative models for planning and decision-making. In the 1960s the system-orientated school started viewing the company as an open system interacting with the environment. Then in the 1970s the innovation-oriented school and contingency management school were established. Structural contingency theory was a follow-on from the contingency management school and is the focal theory of this research. In the 1980s the Japanese school was established and consisted of new approaches to human relations and production efficiency. Then in the 1990s the eco-management school was created with strategies and approaches for environmental improvement (Holt 1999).

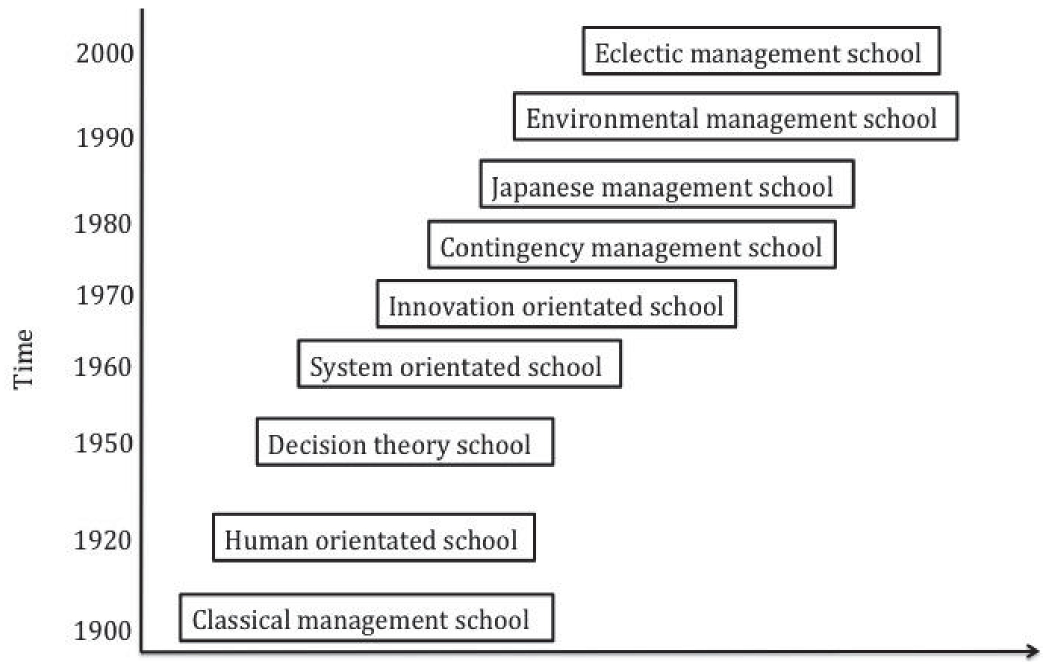

Figure 2.2 Progression of management & organisation theories & schools 1900 – 2000

Source: adapted from (Holt 1999)

2.2.1 Classical management & human orientated schools

The classical management school is empirically established and is characterised as being highly structured with an emphasis on the formal organisation. Taylor (1913) stated an organisation as a system of independent parts and argued there is only one 'best' way to organise these parts. This idea of one 'best' way relates to scientific management, where it is considered human resources can be utilised to create the 'economic man' and where human resources can be utilised in the same way as physical resources (Holt 1999). The limitations of the classical management approach became apparent and subsequently the approach progressed, where the organisation became defined as a system of interdependent and interrelated parts. The human-oriented school came about in the 1920s and 'is characterised by a low degree of structure, with an emphasis on informal organisation, participative leadership and self-control' (Holt 1999 p. 137). The human-oriented school was established from empirical research on the 'social man' and was based on the needs, perceptions and feelings of human beings with an emphasis on satisfying the needs of individuals (Heyel 1939).

2.2.2 Decision theory & system orientated schools

The decision theory school came about in the 1950s and involves building models for planning and decision making (Bolman & Mote 1968). The emphasis is on using quantitative analysis to determine the most efficient use of resources. There is also a focus on profit and utility maximisation (Holt 1999). Knowledge continued to progress and around 1960 the system-oriented school emerged where it was seen that no component of an organisation can be viewed in isolation, and each part of an organisation was interrelated with the other parts. The organisation is seen as an open system with a focus on objectives and the ability to respond to opportunities and threats from the external environment (Holt 1999). This thinking led to the scientific theory of organisations with the understanding that organisations can be viewed as either open or closed systems. This dichotomy of open-closed gives rise to the first truly scientific theory of organisations – open systems theory (O'Connor & Martin 1989).

This conceptual theory explores organisational science and tends to be best understood when its component parts are analysed in relation to the whole. All systems have interdependent parts, and when they operate together, their systemic interaction is toward some goal or end state (O'Connor & Martin 1989). Open systems theory outlines that an organisation is interdependent with its environment as opposed to dependent or independent. One key principle of open systems theory is that an interdependent organisation can be achieved through obtaining information, through interacting and through being aware of the external environment. Another important principle of open systems theory is that it's believed that the system will degenerate unless there is active management, where there is constant adaption to environmental change through constantly balancing and maintaining stability. The open systems concept is important as it helps to provide an understanding of how an organisation interacts with its external environment.

Taylor (1947) highlighted that many industrial-type organisations are fairly self-contained entities and have no need to constantly interact with their environment because the environment is usually stable or presents no surprises. This isn't necessarily true for most organisations as the majority of organisations, particularly those in dynamic industries i.e. construction, consumer electronics and personal computers, the environmental factors are always changing. Some large organisations have economies of scale in process-based industries, i.e. manufacturing, that have little requirement to interact with the environment. However, for the majority of organisations interaction with the external environment is important for long-term survival.

Open systems theory highlighted the importance of an organisation being aware of the external environments outside the boundary of that organisation. There were limitations with the scientific management school of thought as it still held the notion that in each environment there was a single organisational structure that would be successful and able to meet the needs of the environment (O'Connor & Martin 1989). Mintzberg (1981) provides another set of knowledge to the area of organisational theory when he outlines five 'natural clusters' of structural configurations. The five configurations are: simple structures, machine bureaucracies, professional bureaucracies, divisionalised forms and adhocracies. 'Each configuration has its own attributes, which determines the coordination that the organisation is capable of the central purpose of structure is to coordinate the work divided in a variety of ways; how that coordination is achieved dictates what the organisation will look like' (Mintzberg, 1981 p. 104).

Mintzberg (1981 p. 114) argues, 'when these characteristics are mismatched, the organisation does not function effectively and does not achieve a natural harmony.' Therefore, the characteristics and the structural configuration are important in achieving an ideal fit between the organisation's structure and its environment. 'If managers are to design effective organisations, they need to pay attention to the fit,' (Mintzberg, 1981 p. 114). It is important to understand Mintzberg's configurations in order to understand how organisations interact with the external environment. This idea around 'fit' leads into contingency theory, which will be discussed in greater detail in the following section.

2.3 Contingency management school

Contingency theory was first developed in the early 1960s, around the same time as the open systems theory of organisations (Holt 1999). Contingency theory followed on from the ideas of open systems theory where the uncertainties an organisation faces in its environment are variables the organisation can neither control nor predict (O'Connor & Martin 1989). The idea of uncertainties began to be applied to organisations, and this is the basis for structural contingency theory. Scott (1981) notes that contingency theory remains the dominant approach to organisation design as well as the most widely utilised contemporary theoretical approach to the study of organisations.

Contingency theorists rejected classical management approaches and the idea that there was only one 'best' way of structuring and managing an organisation (Burns & Stalker 1961; Donaldson 2001; Lawrence & Lorsch 1967). Instead its argued that the most suitable structure is contingent or dependent upon particular circumstances. Organisations are affected by a number of contingencies including size, strategy, environment and technology. These contingencies are responsible for developing the specific structure and activities of an organisation. When there is a mismatch between the contingent variables and the structure, the organisation will achieve lower performance (Hicks, McGovern & Earl 2001). Moreover, if any of the contingencies change the current structure of the organisation is 'out of fit' and must undergo structural change to regain 'fit' between the contingencies and its structure (Caves & Porter 1977).

Galbraith (1973) summed up the fundamental principles of contingency theory applied to the design of organisation structures as:

- There is no one best way to organize
- No single way of organising is going to be equally effective with another

A number of critics of contingency theory argue that organisations which deviate least from the most favourable structure will be more effective. This argument dates back to classical management theory where there is one ideal organisational structure for all organisations and goes against the essence of contingency theories which assert there is no best way to structure an organisation. Over the years contingency theory has lost some of its original brilliance, and contingency theorists have been relatively silent about these claims. Nevertheless contingency theories' primary mechanisms of structural adaption to achieve increased organisational performance have remained significant over the years.

The theory was different to previous management theories as it recognised that there are inevitable changes in the environment and an organisation must adapt its structure to suit these environmental factors in order to survive. In other words, the contingency resulted in the structure. Early theorists studied these circumstances and treated the factors as a number of widely accepted contingency variables. The key contingencies highlighted in the literature are size, strategy, environment and technology. The following section will review size, strategy and environment, where environment is highlighted as the most important contingency for this thesis, as it leads into structural contingency theory, which will be covered in detail later in this chapter.

2.3.1 Size as a contingency

Size in relation to contingency theory typically refers to the number of workers in an organization – though it can also include geographic spread, turnover or market capitalisation. Blau and Schoenherr (1971) argued that as organisational size increases, structural differentiation also increases but at a decreasing rate.

These findings suggest that structural differentiation becomes more complex. In organisational terms, complexity consists of three measures:

- Horizontal Differentiation
- Vertical Differentiation
- Spatial Differentiation

Horizontal differentiation describes the number of departments and the degree of specialisation within the organisation. Vertical differentiation refers to the layers of management in the hierarchy, the number of subordinates and the span of control. Spatial differentiation is the geographic spread, and the physical separation of facilities and personnel. Blau and Schoenherr (1971) suggest that as organisational size increases, structural differentiation and complexity also increase. Therefore, the structure of an organisation changes because of the contingency of size.

2.3.2 Strategy as a contingency

Strategy is another contingency that can influence the structure of an organisation. When organisations grow and increase their product lines, separate business units or divisions are created for each product line. This implies that a strategy to produce and supply a new product or service will require its own supply line, and in most organisations this would be facilitated with a new decentralised division dedicated to this strategy. This results in an increased level of decentralization and in turn changes the structure of the organisation (Chandler 1962). Using Mintzberg's organisation configurations this structural change would be from a machine bureaucracy to a multidivisional structural form for each of its product lines. It can be concluded that the structure of an organisation changes to follow different strategies.

When expanding the strategy contingency to organisations that are multinational enterprises, the contingency has even greater effect on the organisational structure. Multinational enterprises operate across national borders and in a number of countries. This generally leads to a high degree of capital and management allocated to its strategy. When an organisation plans to expand its operations, the structure of the organisation is determined by its strategy for expansion. Where an organisation can decide to maintain decision-making power with the parent through a centralized structure or if its wants its decisions to remain with managers in the overseas divisions, a decentralised structure may be more appropriate. This demonstrates that the structure of an organisation is dictated by the contingency of strategy.

2.3.3 Environment as a contingency

Environmental uncertainty is a key aspect to structural contingency theory and adopting the appropriate organisational structure can assist in managing that uncertainty. Burns and Stalker (1961) explored the effects that the environment had on organisational structure when considered as a contingency. Their findings concluded 'mechanistic structures are appropriate for stable environments and organic structures are appropriate for fast changing, turbulent, dynamic environments' (Burns & Stalker, 1961 p. 161). The balance between an inflexible structure and a flexible structure was analysed in their research and was found to be directly related to the environment that the organisation operated in.

When referring to Mintzberg's configurations, Burns & Stalker's idea of mechanistic and organic structures could be referred to as bureaucracy versus adhocracy. Mechanistic and bureaucratic structures are associated with organisations that have strict corporate structures and have a hard time dealing with sudden changes in the external environment. Organic structures are ideally suited for adhocracy configurations as they are highly adaptable and can make changes quickly to suit the external environment. Organic structures are also suited to divisional forms as divisional structures are flexible and because sub-units have broader capacities and their product or regional focus helps them react more quickly to local, idiosyncratic threats and also to opportunities. This highlights that environment is another contingency that affects the structure an organisation adopts (Blau and Schoenherr 1971).

Lawrence and Lorsch (1967) found a relationship between the external environment and the internal degree of differentiation and integration in the organisation. They outlined that in complex environments there was a larger degree of differentiation within the organisation. They took the view that organisations with integrative devices would be able to achieve both high integration and high differentiation, and that these would also result in high performance (Lawrence & Lorsch, 1967). As a result, the structure would adjust to suit this requirement for greater coordination, and it was found that the nature and pace of the environment resulted in the structure of the organisation changing. Lawrence & Lorsch (1967) concluded the greater the certainty of the environment, the more formalised the structure of the subsystem. From their findings one can conclude that the external environment is another contingency that influences the structure of an organisation. The environmental contingency also leads into structural contingency theory, which is of importance to this thesis and is covered in detail in the following section.

2.4 Structural Contingency Theory

Structural contingency theory proposes there should be a fit between the organisational processes and the environment – where company models (configurations) that match the environmental requirements should perform more successfully than those that don't (Burns & Stalker 1961; Lawrence & Lorsch 1967). Early work of Burns & Stalker (1966) and Lawrence & Lorsch (1967) developed the theory, and later theoretical developments helped explain those results (Thompson, 1967; Galbraith, 1973). Structural contingency theory states that the most effective organisational structure is that which fits those variable contingencies with which the organisation has to deal (Donaldson 2007). The theory posits that organisations will be effective if managers fit the characteristics of their organisation, such as its structure, with contingencies in their environment (Donaldson 2001).

Under-performing companies may decide to adopt a new business model (configuration) that better fits their environment. Research indicates that it requires significant capital costs and time to establish structural changes in organisational configurations and that as a result companies rarely undertake the process (Caves & Porter 1977). The theory draws specifically from contingency theory, which argues that there is no best way to design an organisation and that no theory or method can be applied in all circumstances (Thompson 1967).

Structural contingency theory extends on contingency theory in relation to how organisations need to continue to evolve by ensuring their organisational structure fits the relevant internal and external environmental contingencies in order to maintain successful performance. The theory was different to previous management theories as it recognised that there are inevitable changes in the environment and that an organisation must adapt its structure to suit these environmental factors in order to survive. In other words, the contingency resulted in the structure. The heart of structural contingency theory lies in how a static state of fit between structure and contingency results in high performance, though Galunic & Eisenhardt (1994) challenge this by outlining that, through being static, structural contingency theory fails to deal with organisational change and adaptation. Merton (1968) describe that structural contingency theory lies within a functionalist tradition of social science as environments change, and organisations constantly adapt and change from one fit to another over time.

There are a number of advantages to structural contingency theory. Firstly, its central focus is on adaptation and responding to uncertainty in the external environment. Adaptation to the environment is an important concept as organisations that are flexible and able to adjust their structures to suit the environment have a greater chance of high performance compared to organisations that do not adapt to changes in the environment. Secondly, structural contingency theory inspires open-minded thinking and seeks many alternative solutions to achieve an alignment between environmental contingency and organisational structure. Contingency theory has been considered to be static in nature and proposed a static state of fit of the organisational structure to the environment. However, as environmental contingencies are constantly changing it is argued that the structure becomes redundant relatively quickly.

2.4.1 Limitations and application to other disciplines

Structural contingency theory focuses primarily on single organisations where the focus is on only one organisation's interaction with its environment. The external environment is not exclusive to one organisation and ultimately impacts many organisations. This brings about the idea of the application of structural contingency theory to a network of organisations. This idea of applying structural contingency theory to SCM and in prefabricated timber systems provides the basis of this thesis. The following section reviews the literature of structural contingency theory applied to SCM.

2.5 Applications of Structural Contingency Theory to supply chain management

A number of studies have looked into streamlining inefficiencies in multi-dimensional supply chains (Birou, Faucet & Magnan 1998; Brewer & Hensher 2001; McAfee, Glassman & Honeycutt 2002; Stuart 1997). Stonebraker & Liao (2004) highlighted the importance of fit, alignment, and consistency to the integration of supply chain activities, though relatively few studies have used structural contingency theory to explain logistics or SCM. Persson (1982) demonstrated the value of structural contingency theory in explaining the organisation of the logistics function according to the complexity of the task. Pfhol and Zollner (1987) was one of the original studies to actually use contingency theory to explain the organisation of the logistics function. Forster and Regan (2011b) and Premkumar et al. (2011) are two other studies that utilise structural contingency theory for the purpose of explaining logistics and SCM. Daugherty, Ellinger & Rogers (2007) showed that through initiating programs that customers neither value nor want, firms risk potentially wasting valuable time and resources. This means that the firms are developing organisational structures that don't fit customers' needs and wants (external contingencies), which in turn leads to a waste of time and resources (reduced performance).

Flynn, Huo & Zhao (2010) argued that, when applying structural contingency theory to supply chain integration (SCI), the individual dimensions of SCI should be aligned in order to achieve the best performance. This means the entire supply chains or business networks should be structured in such a way as to achieve an ideal fit to best suit the external environment. This application of structural contingency theory to an entire supply chain develops the ideas around how groups or networks of organisations can collectively change their structures to better suit the environment in which they operate. Wong, Boon-itt & Wong (2011) undertook research into the use of multidimensional SCI and performance constructs to develop a comprehensive model and theory of the contingency effects of environmental uncertainty. This study lays the foundations for the development of a contingency theory of supply chain integration (Wong et al., 2011).

Robins & Barwell (2007) stated that in order to improve supply chain performance for functional and innovative products a firm must change organisational characteristics and organise their supply chain drivers to form an efficient and responsive supply chain. Lee (1981) developed a framework that incorporated organising supply characteristics into agile supply chains, known as risk hedging, dependent on internal and external contingencies (demand uncertainty). Stonebraker & Liao (2004) were among the first to define and posit the relationships between the strategic and environmental contingencies and the dimensions of integration of the supply chain. Their study made an initial attempt to provide a contingency theory foundation and model of the integrated supply chain. It followed on from recent analyses, and addressed supply chain integration as a continuous and multidimensional variable. They also outlined that effective supply chain integration will likely be tied to a wide range of environmental, strategic, organizational, human, and operations variables. For efficiency and effectiveness**,** a fit must exist between a specific supply chain configuration and the strategic and environmental conditions (Stonebraker &

Liao 2004). One limitation of Stonebraker & Liao's (2004) work is that they have not developed or operationalised a high confidence test of their model. It is through testing the model that they would be able to establish where the greatest integration efforts lie and thus to focus on the most effective approach to integrate an activity in a particular situation.

2.6 Conclusion

This chapter has reviewed organisational theory and the development of knowledge up to structural contingency theory. Structural contingency theory asserts that there should be a fit between the organizational processes and the environment. It outlines that company models (configurations) that match the environmental requirements should perform more successfully than those that don't (Burns & Stalker 1961; Lawrence & Lorsch 1967). When applied to the supply chain the theory highlights that the supply chain should be structured in a way to achieve the best fit with the environment. There is limited research on the application of structural contingency theory to SCM and in particular ETO products. It was established in chapter 1 that organisations along the supply chain for prefabricated timber systems are set up predominantly for the residential construction market. According to structural contingency theory, if these organisations and in turn the performance of prefabricated timber systems are going to compete in the non-residential market, which is a different environment, the organisations and supply chain as a whole will need to change structure to suit the unique needs and expectations of the different environment. These unique needs and expectations of the non-residential market are covered later in this thesis.

Chapter 3 Supply Chain Management & Engineered-to-order products

3.1 Introduction

This chapter provides a review and analysis of literature on the SCM concept. It follows on from Chapter 2 which reviewed organisational and contingency theories. When applying structural contingency theory to the supply chain, the individual dimensions of the supply chain should be aligned in order to achieve the best performance (Flynn, Huo & Zhao 2010). Tommelein, Walsh & Hershauer (2004) describe SCM as one of the leading process-improvement, cost-saving, and revenue-enhancing business strategies practiced in today's business world. This chapter reviews and critiques the literature surrounding key themes in SCM namely, production, distribution, strategic procurement and industrial organization economics (London 2004).

From these key themes, strategic procurement is highlighted as the most relevant to this thesis – as strategic procurement incorporates strategies such as supply chain integration. Concepts such as strategic alliances, partnering and vertical integration are addressed in detail. SCM literature in both mainstream management and construction is reviewed. This is important to address both areas and highlight the differences as SCM literature and strategies used in process-based industries (i.e. manufacturing) are not easily transferable to project-based industries (i.e. construction). Prefabricated timber systems are unique in that they are a manufacturing supply chain in the project-based construction industry. Being an Engineered-To-Order (ETO) product each product passes a design stage, which leads to further complexities. The final section of this chapter reviews SCM literature related to ETO products and, in particular, strategies used to improve the performance of these products.

3.2 Background and key themes in SCM

SCM is a broad research area with a number of different interpretations, and has been adopted in manufacturing process-based industries as well as the project-based construction area. The term SCM was believed to be first coined in 1982 by Keith Oliver, a management consultant (Laseter & Oliver 2003). Day (1998) outlines that SCM research is fragmented and there is a lack of consensus on key themes within the area. This is primarily due to the number of different ways the supply chain concept can be interpreted. Practically every product made for a customer represents the cumulative effort of multiple organizations. For example, manufacturing supply chains for consumer goods in a process-based industry vary considerably from construction contractors in project-based industries (Holzemer, Tommelein & Lin 2000). In process-based industries, manufacturing runs and product demand are relatively constant, whereas construction projects are unique and have different demand requirements. Day (1998) attempted to divide the supply chain concept into a number of key areas, hard, soft, tight and loose. Following on from Day's contribution, a number of authors (London 2004; London & Kenley 2001; O'Brien et al. 2009) outlined the major themes within SCM literature and categorised them into four key areas:

- Distribution
- Production
- Strategic procurement
- Industrial organisational economics

Each of these themes interprets the supply chain in a different way and the literature has studied the key themes from both a manufacturing and mainstream management perspective as well as from a construction perspective. Research from both mainstream management and construction for each of these four themes will be addressed to highlight how SCM is applied differently to the two areas.

The literature offers a number of definitions for SCM; some of the more widely used are outlined below. It is also important to highlight the difference between a supply chain and SCM. A supply chain is defined as 'a network of organisations that are involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services in the hands of the ultimate customer' (Christopher 1998 p. 15). Mentzer et al. (2001) expanded on this definition by outlining that a supply chain is 'a set of three or more entities directly involved in the upstream and downstream flows of products, services, finances, and/or information from a source to a customer' (Mentzer et al., 2001, p. 4). A supply chain encompasses all the various activities associated with the flow and transformation of goods from the raw material extraction stage through to the end user. Material and information flow occurs both up and down the supply chain (Azambuja & O'Brien 2009).

SCM is defined as 'the management of upstream and downstream relationships with suppliers and customers to deliver superior customer value at less cost to the supply chain as a whole' (Christopher 1998 p. 15). Mentzer et al. (2001, p.18) developed a more comprehensive definition of SCM and that includes the idea that it improves long-term performance of companies and not only superior value to customers: 'the systemic, strategic coordination of the traditional business functions and the tactics across these business functions within a particular company and across businesses within the supply chain, for the purposes of improving the long-term performance of the individual companies and the supply chain as a whole'. For this research it is important to highlight the difference between the supply chain and SCM. The supply chain is really the avenue for goods and services to flow along and SCM is focused towards managing and attempting to control the supply chain for the benefit of one or more parties along the chain.

3.2.1 Distribution

SCM from a distribution perspective focuses on the physical distribution of materials and information flow throughout the supply chain. It was spawned primarily out of logistics and also encompasses marketing. The bullwhip effect is central to distribution, where if an issue occurs in one section of the supply chain it has the potential to expand and propagate further downstream. Christopher (2011) is considered one of the key proponents in the logistics field. His research successfully helped bring SCM to the forefront of business strategy. His focus was particularly around the efficient movement and storage of materials through integrated and well-coordinated supply chains. These strategies helped create competitive advantage and support customer focus for businesses. Concepts such as time, compression and transportation optimisation models (Wantuck 1989) are keys in the distribution theme and have the primary goal of improving the flow of information and logistics across the supply chain. London (2004) argued that these concepts were primarily rigid mathematical models that were only as reliant or useful as the quality of data used, which meant they were relatively limited in their ongoing usefulness to businesses.

The distribution theme when related to construction is focused towards the management of materials and information on the construction site. In a construction sense, logistics 'comprises planning, organisation, coordination and control of the materials flow from the extraction of raw materials to the incorporation into the finished building' (Clausen 1995, p. 15). The key objective in this theme is around establishing a relationship between improved management of materials across the supply chain and site productivity. Agapiou et al. (1998) showed that the head contractor and suppliers have a critical role to play in the improvement of material and information flows in the construction supply chain. They suggested that improvements could be made through long-term relationships and greater communication between parties. Moreover, the involvement of suppliers early on in the project lifecycle (i.e. design development) can help improve information flows through valuable input from suppliers, which can also lead to cost savings and increased productivity. Agile construction is another model that can help improve flows of goods and information across the construction supply chain. It has been promoted as a way of gaining competitive advantage in increasingly competitive global markets. Its key focus is around responsiveness and flexibility and is part of a shift in business paradigms towards one which places increased emphasis on the customer (Barlow 1998).

3.2.2 Production

Production theory and in particular lean production has had a significant influence on SCM (London 2004). Lean production is focused towards customisation and high volume production with the aim of delivering customers exactly what they need, at a time they need it. The primary concept of production is the just-in-time (JIT) concept established by Toyota, in particular Ohno, an executive from Toyota – widely considered to be the father of lean production (London 2004). Womack, Jones & Roos (1990) published what is regarded as the seminal text in lean production titled 'The Machine that Changed the World.' They conducted a study on the Toyota Production System (TPS) in the late 1980s. JIT was a key concept from the TPS and was directed towards providing only the necessary items at the right time and place – no less, no more (Nischisguchi 1994). Lean production relies on the use of mass production, particularly where unskilled labour can perform small tasks over and over under the direction of managers. It helps drive cost and time efficiencies and is in stark contrast to traditional craft production, which requires skilled labour working in collaborative environments on complex products.

The construction industry, in particular the supply chain and production system, has been seen to be lacking integration (Vrijhoef & Koskela 2000). Vrijhoef & De Ridder (2007) suggested that by shifting construction from a project-based environment towards a more repetitive and integrated approach is a way to potentially solve the myriad of problems and deficiencies that exist in the construction industry. A number of UK construction industry research reports have been undertaken with the aim of transforming the construction industry into a 'manufacturing process' (Egan 1998; Latham 1994). Aouad (1999) developed the Generic Design and Construction Process protocol, which is a model that treats the construction industry as a production process, where a single process map was used for all phases of the industry. O'Brien (1998) outlined that SCM has the potential to make the supply chain more cost efficient, where his research looked into how subcontractors and suppliers affected the costs, scope changes and schedule overruns. His findings outlined that adopting

JIT models from process based manufacturing industries to the construction industry is difficult due to the project-based nature of the construction industry.

Vrijhoef & Koskela (2000) highlighted that the lagging productivity and increased economic weight of the supply chain in construction is an issue that needs to be addressed. They came up with three main conclusions. Firstly, along the construction supply chain there are a number of processes that create large quantities of waste. Secondly, most of the issues occurring in the supply chain are actually caused in another stage of the construction supply chain when they are discovered. Thirdly, the waste and certain problems (i.e. time and cost overruns) are typically associated with lack of imagination or foresight in the control of the construction supply chain. In Australia time and cost overruns, quality deviations and poor health and safety continually plague construction projects (DIST 1998). There have been calls for improved collaboration, integration, communication and coordination between customers and suppliers throughout the construction supply chain (Egan 1998; Latham 1994). Lean construction was established as a potential way of addressing these issues in the construction industry. The central themes of lean construction are around eliminating waste and improving workflow in the construction. Lean construction comes from a long history of production management thinking and Ballard & Howell (1999) outline that lean construction offers a new way to organise production in construction.

Aside from its proposed benefits, the lean construction movement has endured a lot of criticism around applying the lean concept from manufacturing with the contextualisation needed for the construction industry. 'Lean construction researchers, in their quest for production efficiency, in many cases have forgotten that organising and controlling the market on a very wide and deep scale was instrumental in lean implementation' (London, 2004 p. 72). Green (1999) also highlighted a number of issues in lean construction. His research supported the notion that lean construction failed to provide adequate contextualisation from manufacturing to its application in the construction industry. He also outlined the human (labour) costs and associated issues in lean construction. He believed that it incorporates exploitative practices by both organisations and government through repression of independent trade unionism, increases in pollution and congestion and exploitation of labour. Employees were subjected to army-like treatment where they were under constant surveillance, forced to move away from their families and required constantly to meet unrealistic production targets. It is important to highlight that large producers that successfully implemented lean production did so primarily because of highly organised governance structures. In Japan it was known as *keiretsu,* where subcontractors were organised into hierarchical clusters of tightly-tiered structures (Nishiguchi, 1994).

3.2.3 Strategic Procurement

In the 1980s a number of authors such as Lamming (1992) and Porter (1985) began viewing the supply chain from a strategic perspective. These ideas about viewing the supply chain strategically formed into strategic procurement. Many manufacturing organisations were typically vertically integrated with numerous layers of management. In order to meet ever changing market demands organisations have restructured to form a 'network', where the supply chain is an extension of the organisation (Christopher 2011; London 2004). This concept of business networks is described as relationships between businesses where the chain of connectedness is without limits and can span several relationships that are indirectly connected (Bechtel & Jayaram 1997). Effective coordination and collaboration between all the parties involved in the supply chain, and tight-knit business relationships, are central to the success of the supply chain network.

Strategies such as partnering, strategic alliances, joint ventures are keys to the creation of these business networks. 'Performance is no longer affected by a single firm. Rather, performance of all members involved contributes to the overall performance of the entire supply chain' (Chen & Paulraj, 2004 p. 122). The ability of firms to structure and align themselves with stages up and downstream (i.e. wholesalers, employees and customers) determines the success of the networks. Lamming (1992) developed a process called lean supply, where through partnerships and strategic alliances lean production was able to occur. His research was undertaken within the automobile industry, where he found lean supply is difficult to achieve due to the nature of competition in markets. Lean supply requires complete trust and collaboration between companies, which is difficult when companies are involved in a number of supply chains and typically reluctant to share their intellectual property with companies up and downstream (Tommelein, Walsh & Hershauer 2004).

The strategic procurement concept is important to the prefabricated timber industry in Australia. Companies involved in the production of prefabricated timber structural systems presently compete against one another where they could be working together to create supply chains that can compete against supply chains of substitutes (i.e. prefabricated concrete and steel). Strategic procurement is the central theme of this thesis and a more detailed review of strategic procurement area in SCM will be performed later in this chapter in section 3.3. This will provide a lead-in to SCM literature and ETO products and then structural contingency theory and how it can be applied to SCM and in turn to the organisations along the supply chain for prefabricated timber systems.

As well as in manufacturing, strategic procurement has been used in the construction perspective. Using evidence from the UK construction industry Cox, Ireland & Townsend (2006) argued that there's a severe failure among clients, contractors and suppliers to understand the power and leverage conditions unique to the construction industry. This results in them having unachievable commercial objectives and prevents them realising operational goals. They also argue that these problems are compounded by the aforementioned industry reports (Egan 1998; Latham 1994) as they unthinkingly advocate the adoption of approaches that have worked in one industry (i.e. manufacturing) in the construction industry without fully considering the demand, supply and power circumstances unique to the construction industry. Cox and Townsend (1998) went as far as to say: 'It is our view that if the Latham report, and the somewhat naïve research industry into automotive partnerships and lean and agile manufacturing process that it has spawned, had devoted more time to analysing and understanding the properties of the unique supply chains which make up the complex reality of the UK construction industry, a greater service might have been done to value improvement in construction.'

In response to this, Cox and Townsend (1998) developed the Critical Asset and Relational Competence Approach for Construction SCM, which relies on the clients controlling the supply chain. The crux of their model is that clients first and foremost understand the underlying structural market characteristics of their own particular supply chain and then develop contingent approaches to procurement and integration based on this knowledge. Love, Irani & Edwards (2004) developed a seamless project SCM model where individuals and teams work together at the same time, as opposed to sequentially, to design and develop both product and process. The successful implementation of the model into practice requires a person in charge who has the capacity to coordinate and integrate activities and resources throughout the whole procurement process.

3.2.4 Industrial organisational economics

The industrial organisation perspective is different from the other three themes in supply chain research in that the focus is on the supply chain as opposed to SCM, and the unit of analysis is the industry as a whole as opposed to a product or individual organisation (London 2004). The industrial organisation perspective of supply chains analyses the system of supply chains (New 1997). The application of industrial organisation perspective to supply chains was also influenced by systems theory – where to understand any part of a system, you have to study the whole system (Boulding 1985). There are considered to be two key schools of thought within industrial organisation economics. The first is the 'economics of organisations' that is based on the notion that organisations have production costs, and administrative and transaction costs. Transaction costs determine how companies organise themselves within an industry – when transaction costs are low and production costs high, the companies purchase products from the market. When transaction costs are higher than what a firm can produce products for themselves, other factors come into consideration (i.e. ensuring supply or quality), and then they will vertically integrate into production. Williamson (1985) coined 'transaction cost economy' as the term for this and expanded the concept over time. The other school of thought in the industrial organisation economic field is the 'knowledge based' view where it is seen the boundaries of a company are influenced by the need to gather, coordinate and communicate knowledge.

Industrial organisation also deals with the performance of organisations and the effects of market structures on market conduct, including pricing policy, restrictive practices and innovation (Bancock, Baxter & Davis 1998). Grimm (2008) outlined that industrial organisation adds a lot of value to the supply chain concept and can help research in the area develop both in quality and stature. Ellram (1991) undertook research that looked into different SCM relationships that are suited to certain situations based on an industrial organisation perspective. Ellram analysed the advantages and disadvantages of vertical integration. Her research was one of the first pieces of work to apply transaction cost economic theory and industrial economic organisation with SCM. Ellram's findings were that situations that were favourable to SCM included recurrent transactions requiring highly or moderately specialised assets and operating under moderate to high uncertainty.

Nischiguchi (1994) merged industrial organisation theory to the supply chain concept, with a focus on lean production. His research looked into network sourcing in the Japanese manufacturing industry and made a number of important contributions to the field, including descriptions of the economic and organisational structure of the Japanese manufacturing industry. His contributions have supported the notion that industry structure is an important consideration when implementing lean production techniques. Contextualisation is important although it was conducive to automotive and electronics industries in Japan doesn't mean it is easily transferable to other industries. AEGIS (1999) developed a model in Australia specific to construction that contributed to the wider industrial organisation economic concept. The Building and Construction

Industry Cluster model categorises the construction industry into five main sectors including onsite services, client services, building and construction supplies, tools and capital. London (2004) outlined that the AEGIS model was one of the first studies to use industrial organisation economics to understand the supply chain.

Following the review of the four key themes in SCM, strategic procurement is found most relevant to this thesis as viewing the supply chain from a strategic perspective lad to revolutionary changes, and supply chains began rethinking their organisational structures to suit their environments (Christopher 2011). This thinking stems from structural contingency theory – the organisational theory which states there should be a fit between the organisational processes and the environment. As covered in the previous chapter, structural contingency theory advocates that company structures that match the environmental requirements should perform more successfully than those that don't (Burns & Stalker 1961; Donaldson 2001; Lawrence & Lorsch 1967). Applying structural contingency theory to the supply chain, the individual dimensions of the chain should be aligned in order to achieve the best performance (Flynn, Huo & Zhao 2010). The following section covers strategic procurement management in greater detail.

3.3 Strategic procurement management

The strategic procurement perspective is much wider than the lean movement – central to the strategic procurement is business alliances, including partnering, strategic alliances, joint ventures, network outsourcing (London, 2004). Gomes-Casseres (1996) has argued since the 1980s that there's been a substantial increase in close business alliances across all industries. This proliferation of business alliances has been facilitated by a resulting decrease in costs and financial risks. The alliances have also facilitated entry into new markets, and increased innovation and trust particularly in volatile markets (London, 2004). Equally important to business relationships between supply chain members is fostering and creating links with customers. Strategic procurement also helps provide a framework for attaining close, well-tiered customer supplier relationships (Bechtel & Jayaram 1997).

These relationships are all linked to business performance and can impact and influence the capabilities and competitive advantage that an organisation implements. Porter (1985) developed what is known as the 'value chain' – a concept used by companies to help improve their competitive advantage in an industry. The key theme of the value chain concept is around determining appropriate strategies for a company's primary activities (i.e. operations, logistics (inbound and outbound), marketing and sales and service) to allow the company to achieve a competitive advantage in the market. It is around understanding the relationships within the supply chain for the individual organisation's gain – particularly purchasing from and forming relationships with suppliers up and downstream who will help improve the company's competitive advantage. London (2004) explained that Porter's work originates from industrial economic organisation concepts though it is also primarily within the strategic procurement perspective. Implementing strategic procurement strategies successfully can put an organisation in better stead to deal with changes in the environment because the keys to long-term competitive advantage in today's marketplace are flexibility and customer response (Bechtel & Jayaram, 1997).

Supply chain integration has been suggested as a way to potentially solve the myriad of problems and deficiencies that exist in the construction industry (Vrijhoef & de Ridder 2007). Strategic procurement strategies such as vertical integration, partnering and alliances are used to achieve supply chain integration and will be discussed in greater detail later in this thesis. It is important to point out here that construction supply chains differ in many ways from manufacturing, namely they are project-based, fragmented and adversarial relationships are common. The success of SCM is governed by the interaction between organisations within the supply chain and strong feedback linkages and collective learning (Saad, Jones & James 2002).

3.3.1 Partnering & Strategic Alliances

Partnering is viewed by many in the construction industry as a fundamental shift in the way business has been conducted over the past decade (Saad, Jones & James 2002). Many working in the construction industry have endeavoured to improve project quality and performance through closer process integration and SCM. Government sponsored industry reports (Egan 1998; Latham 1994) have described the issue as critical to the construction industry and believe that the introduction of partnering has potential to help address its poor performance issues.

The Construction Task Force report 'Rethinking Construction' highlighted 'partnering involves two or more organisations working together to improve performance through agreeing mutual objectives, deriving a way of resolving any disputes and committing themselves to continuous improvement, measuring progress and sharing the gains' (Egan 1998 p. 12). Strategically, organisations may enter into alliances (a form of partnership) in order to innovate, gain access to new markets, overcome market restrictions, restrict competitors and share risks amongst a number of players (Stanek 2004). Partnering is able to facilitate the unique skills and expertise of each partner and also has potential to ''lock out'' competitors, though partnerships are costly in terms of time and effort to initiate and maintain (Lambert, Emmelhainz & Gardner 1996). Partnerships in supply chains are also able to make resources work more efficiently and lower the environmental impacts of products (Schllephake, Stevens & Clay 2009). Saad, Jones & James (2002) highlighted that the early ideas of partnering and construction revolved around a number of key principles including:

- Agreeing mutual objectives
- Making decisions openly
- Resolving problems in an agreed manner from the outset of the project.

Beach, Webster & Campbell (2005) described that in construction there are two different types of partnering. The first is 'strategic partnering', which is focused on a relationship that is intended to last for a significant period of time and be utilised on a number of projects. In strategic partnerships there is typically a commitment between two or more organisations to achieve specific business objectives by means of maximising participants' resources effectively. The second is 'project partnering', which is focused more on the short-term benefits and is generally limited to a single project. Project partnering can be used on virtually any size project and is based on co-operative relationships between two or more parties who strive for short-term project-related benefits. Brensen & Marshall (2000) have outlined some limitations in relation to project specific partnering's use in the construction industry. These limitations are around the fact as it's an industry that is heavily reliant on repeat business, meaning that one-off project-specific partnering has little benefit in the long term.

Beach, Webster & Campbell (2005) have a similar though slightly more detailed approach in relation to the difference in partnering arrangements compared with Lambert, Emmelhainz & Gardner (1996). Lambert, Emmelhainz & Gardner (1996) highlighted three different types of partnering. 'Type I' partnerships are typically short-term in focus and participants recognise each other as partners on a limited basis. 'Type II' partnerships are focused on a more long-term relationship and have some degree of integration between the activities of the organisations involved. 'Type III' partnerships, which are considered to have ''no end date'' to the partnership arrangement, have a significant degree of integration between the organisations, where typically each sees the other as an extension of their own firm. Lambert, Emmelhainz & Gardner (1996) also developed a model which can be used to determine if a partnership should be established and whether Type I, Type II or Type III should be adopted between the organisations. The model is based on three factors (drivers, facilitators and components), with each factor being broken up into smaller elements to help the decision to create or adjust a partnership. Companies use the model to determine what level of partnership arrangement is most suited to their situation .

Johnston & Lawrence (1988) introduced the idea of a value-added partnership (VAP), which is a set of independent organisations that work closely together to organise and manage the flow of goods and services across an entire supply chain. Johnston & Lawrence (1988) point out that the key to the success of the VAPs is the attitudes and practices of participating managers. It's of critical importance that managers involved understand the relationships along the entire value-added supply chain and that it's important that each link in the chain is as strong as possible. Beach, Webster and Campbell (2005) produced similar results to the work of Johnston & Lawrence (1988) when they undertook a survey by questionnaire of industry practitioners and established that management commitment was considered to be the most important element of successful partnering. A number of authors have outlined the benefits of partnering as an integration strategy and a summary of the literature is presented in Table 3-1 below. These studies have established that reduced upfront/capital costs, reduced defects/improved quality and increased productivity are the most common benefits of partnering.

Table 3-1 Benefits of partnering

	(Egan 1998)	(Black, Akintoye & Fitzgerald 2000)	(Scott 2001)	(Haksever, Demir & Giran 2001)	(Beach, Webster & Campbell 2005)
Less accidents on-site	✓				
Fewer disputes		✓	✓	✓	
Reduced upfront/ capital costs	✓	✓	✓	✓	✓
Reduced construction time	✓	✓	✓	✓	
Reduced defects/Improved quality	✓	✓	✓	✓	✓
Increase predictability	✓	✓	✓	✓	
Increase productivity	✓	✓	✓	✓	✓
Increased return & profits	✓	✓	✓	✓	

3.3.2 Vertical Integration (VI)

Vertical integration (VI) is a fundamental corporate strategy that is of interest to the fields of strategic management as well as organisational economics (Mahoney 1992). 'The idea of VI is anathema to an increasing number of companies. Most of yesterday's highly integrated giants are working overtime at splitting into more manageable, energetic units – i.e. de-integrating. Then they are turning around and re-integrating – not by acquisitions but via alliances with all sorts of partners of all shapes and sizes' (Grant 2007 p. 339) . VI provides an organisation with control over sensitive new technology and capabilities whilst still providing the organisation with the opportunity to increase its efficiency through the use of closer internal communication and coordination of activities (Beach, Webster & Campbell 2005). Harrigan (1984) outlined that the key to using vertical integration is for an organisation to recognise which activities they should perform in-house, how these different activities relate to each other, and how much ownership equity should to be invested (risked). The conventional analysis to deciding how much equity should be invested relates to the efficiency of markets, where if the cost of transacting through the market is greater than the cost of administrating through a firm, then VI is a sound strategy. This thinking stems from transaction cost economic theory (Williamson 1985).

Harrigan (1984) outlined four different VI strategies:

1. *Non-integration* – This is where organisations risk the lowest proportion of their assets in vertical arrangements involving non-integrated controls. This type of VI is typically adopted by organisations that are hesitant to buy specialised assets, need lower break-even points due to underdeveloped demand, or are able to set-up delivery schedules with suppliers up and down stream in the supply chain.
2. *Quasi-Integration* – These VI arrangements place greater amounts of ownership equity at risk compared to non-integration, though this also provides greater flexibility in responding to changing conditions than a contract may provide. The arrangements between organisations take the form of cooperative ventures, minority equity agreements, among others.

3. *Taper Integration* – When firms integrate either forward (upstream) or backward (downstream) but still rely on outside organisations for a proportion of their supplies or distribution. Taper Integration is recognised as a good compromise between desires to control adjacent businesses and a need to maintain flexibility.
4. *Full Integration* – This applies when there is a high degree of internal transfers. Generally this type of VI strategy is best suited in industries where environments are stable, or if outside suppliers and/or distributors are deemed to be inadequate.

Following on from reviewing the different perspectives of SCM in both mainstream management and construction, and analysing strategic procurement, it is important to review different product typologies as the focus of this research is around prefabricated timber technologies. Engineered to order (ETO) product supply chains are of most importance to this thesis as prefabricated timber systems are ETO products. The following section will look into how ETO supply chains differ from other product typologies and what are the key strategies to improve the performance in ETO supply chains.

3.4 Product typology and the supply chain and Engineered to order (ETO)

Beside the different perspectives of the supply chain concept and procurement methods, product type and characteristics play a large part in supply chain configurations. Products can generally be categorised into four main types: Make-To-Stock (MTS), Assemble-To-Order (ATO), Make-To-Order (MTO) and Engineered-To-Order (ETO) (Wortmann, Muntslag & Timmermans 1997). A number of authors provide variations to these four categories. Hoekstra & Romme (1992) outlined the four aforementioned as well as Ship-To-Stock (STS) as another product categorisation, where the decoupling point is located as finished goods in a national company. Gosling et al. (2007) also outlined Buy-To-Order (BTO) as another type of product classification. Porter et al. (1999), following on from Lampel and Mintzberg (1996), categorise manufacturing into five different classes: make-to-stock, assemble-to-order, make-to-order, engineer-to-order and Design-To-Order (DTO). Porter et al. (1999) introduced the DTO classification where design, engineering and manufacturing are incorporated for each new product. Figure 3.1 outlines the various processes involved in the different product types. In particular it highlights that ETO products undergo a design stage, whereas no other product also undergoes this stage. This is key differentiating factor between ETO products and others, where the decoupling point is at the design stage.

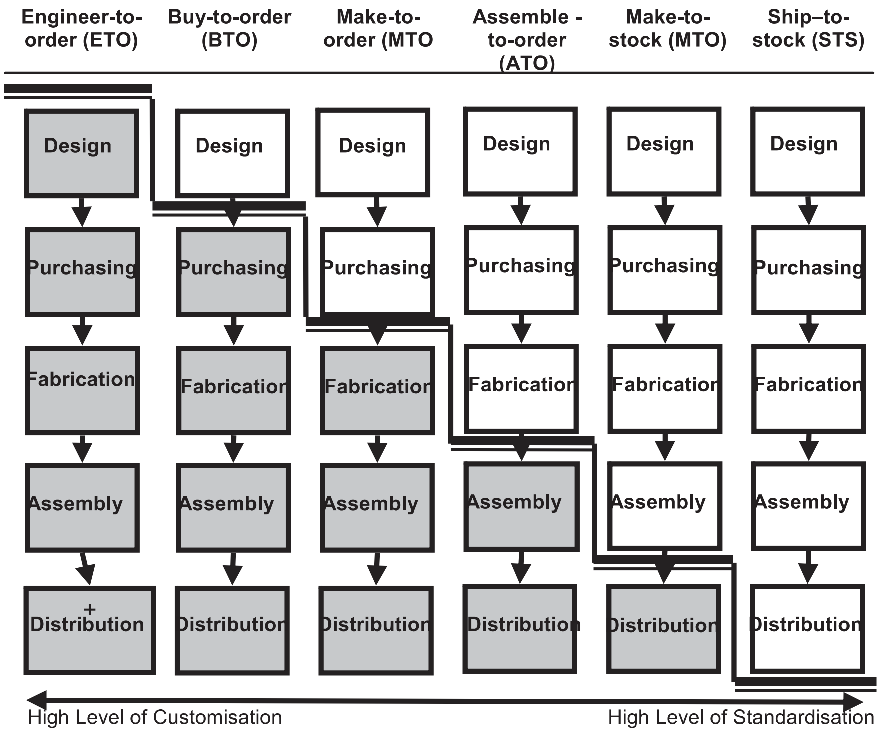

Figure 3.1 Six supply chain structures and processes involved
Source: (Barker 1994)

The decoupling point also plays a large role in the categorisation of different products. The decoupling point is a stock holding point that responds directly to the customer from the part of the supply chain that uses forecast planning. Upstream from the decoupling point all products are produced to forecast; downstream from the decoupling point all products are pulled by the end user (Christopher 2011; Mason-Jones, Towill & Naylor 2000; Olhager 2003). Another important contribution to this body of knowledge is the idea of continuum standards (Lampel & Minztberg 1996). These standards show how the level of customisation and standardisation for key stages of different products (i.e. design, fabrication, distribution, and so on) can be categorised into five stages, namely, pure standardisation, segmented standardisation, customised standardisation, tailored standardisation and pure customisation. Table 3-2 outlines further details on the different product taxonomies from Figure 3.1.

Table 3-2 Characteristics of production management in the product taxonomy

Orientation	Product	Workflow	Resource	Product	Product
Product	**ETO**	**MTO**	**MTO**	**ATO**	**MTS**
Example	Power distribution equipment	Prefabricated electrical receptacle	Cast-in-place concrete	Doors, windows	Bricks, bolts
Top management's focus is on	Customer order contracts	Process innovation	Capacities	Product innovation	Marketing/ Distribution
Uncertainty of operations is concentrated in	Product specifications	Volume of production	Work preparation	Mix of orders	Product Life-Cycle
Complexity of operations is concentrated in	Engineering	Final production stages	Component manufacturing	Assembly	Physical distribution
Middle management's focus is on	Project management	Quality control	Subcontracting, Shop floor control	Master Production Schedule, customer order contracts	Stock control
Information systems for PM are focused on	Support for product engineering	Progress control	Support for manufacturing engineering	Support of material supply and order entry	Support of forecasting and stock control
Nature of IS oriented towards	Generative solutions	Workflow management	Reference solutions	Rules	Decision support

Source: (Wortmann et al. 1997 p. 65)

Through using table 3.4.1 and figure 3.4.1 as a guide, it is determined that prefabricated timber systems fall under the ETO categorisation. Prefabricated timber systems always undergo an engineering design stage and the decoupling point is located at this design stage. This concept of the decoupling point is of particular importance to ETO products and in turn prefabricated timber systems, as it means that early on in the supply chain the customer is involved with the process of product development. The following sections of this chapter will analyse supply chain strategies for ETO products and specifically those within the strategic procurement perspective, and strategies to improve performance of ETO products.

Limited operations and SCM research have occurred to date on the ETO supply chain (Gosling & Naim 2009; Hicks, McGovern & Earl 2001). There has been confusion throughout the literature as to an appropriate definition for ETO supply chain operations (Gosling & Naim 2009). The ETO supply chain is generally associated with large project-based environments such as construction and capital goods. It is characterised as having the 'decoupling point' located at the design stage. This is the case for prefabricated timber structural systems where each system undergoes a unique structural design solution.

3.4.1 SCM Strategies for ETO supply chains

The ETO sector has received much less attention in the literature than any of the other product categories e.g. high volume Make-to-Stock (MTS) (Gosling & Naim 2009). The increased complexity of these products makes SCM more difficult to implement and volumes are lower. Gosling & Naim (2009) outline seven SCM strategies for ETO supply chains. Each of these strategies is used to help improve performance and, in turn, time, cost and quality in the supply chain.

1. Shift between supply chain structures

The strategy of shifting from one product categorisation to another can help improve performance. This can be done in two ways. Firstly, an increase in the ability to customise products in order to meet the ever-changing needs of clients (i.e. MTS to ETO) can increase performance (Hicks, McGovern & Earl 2001; Salvador et al. 2007). Secondly, on the contrary, some ETO organisations are looking to increase the ability to produce modular components and move away from pure customisation. Hicks et al. (2001) showed that this increasing modularisation and standardisation of products can help reduce time and costs.

2. Supply chain integration

Hicks et al. (2001) argued that supply chain integration can help improve performance, though it is more difficult to implement in ETO products, as they are customised uniquely for each project. They also concluded that some lessons can be learnt from the high volume-manufacturing sector, where a decrease in supplier base and long-term relationships can help streamline processes. Hicks et al. (2001) stressed it is important to understand the context of the ETO supply when looking to implement these strategies – in particular understanding the power regime and demand situation is important to consider when implementing supply chain integration strategies (Cox, Ireland & Townsend 2006).

3. Information management

Having timely access to information from downstream suppliers and ultimately the customer helps reduce demand uncertainty and reduce stock-piling of finished goods (Donselaar, Kopczak & Wouters 2001). This concept also relates to the demand-pull against demand push-concept. Little, Rollins & Porter (2000) outlines material resource planning, a tool typically used for production control, is difficult to implement for the ETO supply chain. This is due to the inherent uncertainty in demand and unique product specifications.

4. Business systems engineering

Childerhouse et al. (2003) undertook research on the implementation of business process re-engineering in construction. The re-engineering of traditional business functions was performed across key areas: manufacturing, supply chain integration, customer integration and lead times. This process led to numerous benefits including reduction in cycle times and lead times, increased profit margins, and so on. When applying business process re-engineering to ETO supply chains Cameron & Braiden (2004) encountered issues in relation to lack of risk assessments and to defining the scope of the re-engineering process across the supply chain.

5. Flexibility

Flexibility is an important supply chain strategy for ETO products. A number of different types of flexibility are applied to ETO products and there are synergies and trade-offs associated with them. Types of flexibility include process flexibility, product flexibility, volume flexibility, suppler flexibility, workforce flexibility and assembly flexibility (Holweg & Pil 2001) & Salvador et al. 2007).

6. Time and compression

Implementing time compression strategies to the ETO supply chain can help produce large time and cost savings. Towill (2003) concluded that a 40% time saving on projects can lead to a 25% cost saving. Key time issues highlighted in the ETO sector include tendering, design and procurement (Elfving, Tommelein & Ballard 2005).

7. New product development process improvement

Existing frameworks in the literature are said to be unsuitable for the ETO supply chain. A number of authors have developed new product development processes for ETO products. Caron & Fiore (1995) looked into the integration of logistics and project management in the ETO supply chain and outline the integration of the design and manufacturing is important in the product development process.

After reviewing these strategies to improve supply chain for ETO products, integration is most relevant to this thesis as it forms part of the strategic procurement perspective. These ideas will be followed up to support the model development in Chapter 7.

3.5 ETO company and supply chain models

Throughout the literature a number of authors have outlined various company business models and supply chain models for ETO products. Hicks, McGovern & Earl (2001) outlined that there are four ideal types of ETO company business models. These models were geared toward capital equipment suppliers in the UK, though the processes involved (design, detailing, manufacture/fabrication and installation) are generic for all ETO products. Marjoribanks (2007) and Fabian (2007) developed a number of ETO supply chain models for the steel industry in Australia. Steel has a similar supply chain to prefabricated timber systems so these models are of particular interest to this research and are covered below.

3.5.1 ETO company models

Model 1 – Vertically integrated

Companies that use this model have core competencies in design, manufacturing, assembly (fabrication) and project management. They are responsible for all the processes across the supply chain for an ETO product. The major advantages of this model are the integration of internal processes across the supply chain as well as retaining product and process knowledge. Having in-house technical services as well as manufacturing and fabrication capabilities allows a design to be developed based upon knowledge of internal production capabilities (manufacturing and fabrication). This can help prevent design iterations. Overlapping of the design and manufacturing activities can also help achieve a reduction in lead times. Having a highly integrated manufacturing capability, the potential to value add can be optimised.

There are a number of disadvantages in a fully vertically integrated company including the risk that sufficient orders are not achieved to provide an adequate return on capital. Large capital costs are typically required for vertical integration and this strategy is typically most suited to stable and mature environments (Harrigan, 1984). Typically, this type of company will operate in an assured market, where there is continuous demand and low levels of risk (Hicks et al. 2001). As outlined by Harrigan (1984) in section 3.3.2, non-integration, quasi-Integration and tapered integration are other options available to companies instead of full integration. These levels of vertical integration are more relevant to companies involved in the production of prefabricated timber structural systems in Australia and NZ. This is a new market with limited demand, so a fully vertically integrated model (by one company) may not be the most appropriate and feasible solution in the short term.

Model 2 – Design and fabrication

This model refers to companies that have competencies in design, fabrication and project management. The model is a type of taper integration (Harrigan 1984) where firms integrate either upstream or downstream but still rely on outside organisations for a proportion of their supplies or distribution. This model is recognised as a good compromise between desires to control adjacent businesses and a need to maintain flexibility. Product leadership and competitive advantage is achieved through in-house design in unison with co-ordination of internal and external processes. One advantage of this model is outsourcing of manufacturing, which means they are not as capital intensive as fully vertically integrated companies. However, a potential issue with this model is ensuring adequate supply of resources from the manufacturer. Partnerships/alliances with suppliers downstream can alleviate this potential issue. The balance of power with these partnerships is governed by the volume of demand for particular items, the value, the number of suppliers and potential switching costs Hicks et al. (2001).

Model 3 – Design and construct

This model refers to companies that have core competencies in design, project management and logistics. Manufacturing, fabrication and construction of ETO components is outsourced, and competitive advantage is based upon systems integration. This model retains product leadership through in-house design, and it is important design and construct companies are able to meet stated and unstated customer requirements, through integrating subsystem performance specifications. One issue with this model is that sharing of design information with manufacturers and fabricators may loose potential intellectual property. This may make it difficult to retain product leadership and potential competitors could leverage this in future projects (Hicks et al. 2001).

Model 4 – Project management

This is a model where a company manages contracts on behalf of a client – or in most cases in construction projects as head contractor. The responsibilities of the company involved are initial specification and technical evaluation of tenders from design consultants, suppliers and subcontractors. Once evaluations are completed, recommendations are made to clients/head contractors. This is typically done based on evaluation criteria and in some cases has the potential to encourage or inhibit innovation. An advantage of this model is that the overheads and capital employed are very low and that the company carries little risk (Hicks et al. 2001).

3.5.2 ETO supply chain models (multiple companies)

Marjoribanks (2007) and Fabian (2007) developed a number of ETO supply chain delivery models. These models are focused on companies involved in the production of steel structural systems and are based on a number of companies along the supply chain as opposed to the four models above which were focused on one company. Steel structural systems are an ETO product, similar to prefabricated timber elements. The steel industry supply chain is characterised as being disjointed and fragmented, which is highlighted as a major deterrent to further market penetration – though not as fragmented as the supply chain for prefabricated timber systems in Australia and NZ. The primary goal of these ETO models is to help deliver a seamless process to the head contractor and client, whilst still meeting relevant needs and expectations as detailed earlier in this chapter.

Model 1 – Traditional contracts

This model consists of a predominately informal (contract based) relationship between the designer, detailer and fabricator. The manufacturer and quantity surveyor may also be involved in this relationship. The services/resources of all parties could be offered to a client or head contractor as a complete solution to deliver a product. The price would be a combined value and relationships amongst project members would be through subcontracts. An advantage of this model is that it is simple and requires little to no capital costs, though still with the possibility of achieving time and cost savings. This model is that it is still pretty much common practice, and any savings achieved in one area typically aren't shared amongst members and more importantly doesn't improve performance (time, cost and quality) of the product overall (Marjoribanks 2007). Another potential issue of this model is in relation to the Trade Practices Act and potential implied collateral contracts. This model represents the model currently used by companies along the supply chain for prefabricated timber systems in Australia and NZ.

Model 2 – Sub-alliances

Model 2 is similar to Model 1, in that project members (designer, detailer, fabricator and manufacturer) are arranged under a subcontract scenario with the head contractor. However, there are formal alliances between members and a contractual arrangement is in place by which gains and losses are shared. The existence of the alliance would be disclosed to the head contractor and an advantage of this model is that it might appear more appealing to the head contractor, as they might see it as a genuine way to achieve time and cost savings. However, it may be difficult to transfer time-savings into cost benefits. One major disadvantage of this model for the head contractor is that there isn't an entity that is responsible for the entire process and the supply chain is still organised through a number of separate subcontracts (Marjoribanks 2007). A variation to this model could be a scenario where the head contractor is also an alliance member. The advantage of this is that gains and losses would be shared between all parties involved in the project, so there is more chance of collaborative relationships as opposed to adversarial relationships that are common throughout the industry. This model has been used to date in the steel industry in Australia.

Model 3 – Special Performance Vehicle (SPV)

This model would be particularly suited for an individual project, as opposed to a longer-term model. It would be supported through alliances and partnering arrangements. Partnerships in the SPV would typically be 'Type I' as outlined by Lambert, Emmelhainz & Gardner (1996) who describe these as short-term in focus with participants recognising each other as partners on a limited basis.

Beach, Webster & Campbell (2005) have a similar definition for this type of partnering which they refer to as 'project partnering' and can be used on virtually any size project. It is based on co-operative relationships between two or more parties who strive for short-term project-related benefits. One disadvantage of this model is that it is short-term (project) in nature and it is difficult to be certain that benefits could be accrued.

Model 4 – Special Purpose Company (SPC)

The SPC is a model where a Design & Procurement model is utilised and consortium members are shareholders. The SPC is not a subsidiary of another company, though rather a consortium made up of supply chain members, in which each has an equity share in the SPC. Subcontracts would be let between consortium member shareholders to provide the necessary services to meet the contract with the head contractor. The first advantage of this model is that it offers a single point of responsibility to head contractors and uses subcontractors' insurances. Secondly, it can enhance delivery, whereby it can organise construction programs, design freeze points and payment schedules as well as generally saving time for the project and subcontractors as a whole. Finally, it has the flexibility and capacity to match resources to projects where necessary. However, there are a number of unique disadvantages of the SPC. It doesn't have the brand backing of a separate large entity and typically only one designer, detailer & fabricator will be members in the SPC. Moreover, each shareholder requires equity commitment, and this capital investment could limit potential consortium members

3.5.3 Selection of ETO models

A number of factors affect the selection and success of particular models. Fabian (2006) showed it is important that contractual arrangements are not commercially impractical to the head contractor or client. It is also important that the commercial arrangements utilised optimise the commercial opportunities for those involved more so than being 'business as usual'. Fabian (2006) also described advantages and disadvantages when choosing a particular model as well as considerations relating to individual corporate policies and potential tax considerations. He argued that the suitability of a particular model is more a commercial issue than a legal issue and two key items that would need to be considered are the commercial and financial credibility of the vehicle/model and the willingness of participants to align themselves under its umbrella.

3.6 Conclusion

This chapter has reviewed and analysed a number of different perspectives of SCM both in mainstream management and construction. From this analysis strategic procurement has been established as most appropriate to improve the performance of the supply chain for prefabricated timber systems. Different product typologies were reviewed and it was established that prefabricated timber systems are ETO products, with unique supply chains. Next, strategies used to improve the performance of ETO products were reviewed and it was established that supply chain integration was most applicable to prefabricated timber systems and supply chain integration forms as a key aspect of strategic procurement.

Viewing the supply chain from a strategic perspective led to revolutionary changes, where supply chains began rethinking their organisational structure to suit the environment (Christopher 2011). This thinking stems from structural contingency theory – an organisational theory, which states there should be a fit between the organisational processes and the environment. Structural contingency theory asserts that company structures (business models) that match the environmental requirements should perform more successfully than those that don't (Burns & Stalker 1961; Donaldson 2001; Lawrence & Lorsch 1967). The strategic procurement perspective is key to this research and when combined with structural contingency theory is considered the most relevant to improving the performance of prefabricated timber systems due to the fact the current supply chain for prefabricated timber systems is fragmented and focused on the residential construction market instead of the non-residential market, which has different market needs and expectations.

Chapter 4 Prefabricated timber systems

4.1 Introduction

In this thesis structural contingency theory reviewed in chapter 2 is the major thing, the thing that is being tested. Following on from this the supply chain is the environment in which the theory is being tested; – it was reviewed in chapter 3 – and then prefabricated timber systems is the product involved as a case study to test the theory. This chapter reviews and analyses the literature on Engineered Wood Products (EWPs) and prefabricated timber construction. The Australian and New Zealand (NZ) construction markets are of particular focus and a number of areas are addressed. These include: key prefabricated timber systems that are available and those focused on in this thesis, the size and structure of the different construction markets, and issues preventing their use in non-residential construction.

Prefabricated timber systems offer a lightweight, sustainable structural alternative to traditional forms of construction. In non-residential and multi-storey residential construction throughout Europe prefabricated timber systems have proved to be a viable alternative to steel and concrete. This thesis will focus primarily on EXPAN structural systems, which are made from Laminated Venner Lumber (LVL). Cross Laminated Timber (CLT) and glulam will also be covered. LVL and glulam are the most suitable choices for use in structural applications in non-residential construction, particularly when they are incorporated into EXPAN systems. There is also manufacturing capacity present in Australia and NZ for these products. Perkins & McCloskey (2010) demonstrated CLT is a viable option in Europe, and even though there isn't any manufacturing capacity for it in Australia (a small number of organisations using plywood or glulam presses to make CLT is not considered as manufacturing capacity), it will be looked into in this thesis.

As the Architecture & Design (A&D) industry is responsible for creating specifications for buildings they have a large influence on the materials that are used. Bayne & Taylor (2006) discovered that architects were seemingly more interested to learn about timber and keen to give it a go, compared to engineers who were more reluctant to spend the time to learn and use timber. An architect stated, ''engineers were lazy and reluctant to work with timber because it took longer'' (Bayne & Taylor 2006, pg. 20). This lack of training and expertise in timber design was also cited in O'Connor et al. (2004) study, where engineers in North America were quoted as stating they ''learned little or nothing about wood in school'' (O'Connor et al. 2004). In O'Connor et al.'s (2004) survey, 75% of the architects responded that they felt comfortable designing non-residential buildings in timber. Nolan (2010) supported Bayne & Taylor (2004) and O'Connor et al. (2004) by producing results that industry finds it very difficult to obtain external engineering skill with wood. The issue with this is that a lot of designers aren't aware of what is possible in timber and as a result it takes longer and is more expensive to design.

4.2 An overview of Engineered Wood Products – prefabricated timber systems

EWP, commonly referred to as manufactured wood products, are the main component in prefabricated timber structural systems. EWP are starting to attract interest and substantial growth within the construction sector due to their uniform mechanical and physical properties compared to solid sawn structural timber products (Lam 2001). EWP have great opportunities in non-residential multi-storey construction due to their high strength to weight ratio, light prefabricated nature and inherent environmental attributes. Traditionally, residential construction has been the primary market for structural EWP, where they have been used in houses for a number of applications including bearers, joists, lintels and rafters. EWPs have been developed with the mindset of achieving structural efficiency through using smaller timber sections. This structural efficiency in engineered wood products is greater than that of solid sawn timber as the strength-reducing characteristics inherent in solid sawn timber are either removed or positioned in the engineered member during the manufacturing process so their negative effect is minimised (FWPA 2007). Lam

(2001) outlines that the structural performance of engineered wood is determined mainly by the properties of the particular wood species used, the particular manufacturing process adopted, as well as the quality control processes present throughout the production phase of the material.

Non-residential construction and in particular commercial office buildings typically consist of large open plan spaces with long span floors supported on beams (girders) and columns. LVL and glulam presents as a viable option to be used for the structural systems in commercial buildings. LVL can be either a solid section or prefabricated with a hollow section to utilise new innovative Post-Tensioned (PT) technology. PT improves seismic performance and also the ability to achieve longer spans with smaller beam depths (Palermo, Pampanin, Carradine, Buchanan, Dal Lago, et al. 2010). This PT technology is known as EXPAN and will be one of the key focuses for this research.

CLT in an EWP that has proved to be a successful prefabricated timber system throughout Europe (Ceccotti 2008). It is being earmarked as having the greatest potential to compete with steel and concrete in North America (Perkins & McCloskey 2010). CLT is particularly suited to multi-storey residential buildings, which have short span floors supported on walls from the previous floor. Smith (2008) highlights there are limitations to the unsupported spanning capabilities of CLT – making it unsuitable for open plan structures on its own – though hybrid structures combining CLT and LVL or glulam could potentially be an effective design option for use in non-residential construction (Gagnon & Pirvu 2011). CLT and glulam hybrid structural systems have been successfully used on a number of projects throughout Europe e.g. the Norwich Open Academy and the Kingswood Locality Hub in the UK.

4.2.1 Glulam

Glue laminated timber (glulam) is an engineered wood product consisting of small sticks of wood that are laminated together with an adhesive. The sticks are laid in the same grain direction to give superior consistency in strength and stiffness, when compared with sawn timber. It is one of the oldest and most resource efficient EWPs available and it is believed to have originated in Germany in 1900 (FWPA, 2007). Glulam is used widely through Europe, North America and Japan (Lam, 2001) and was first introduced into the Australian Market in the 1950s. Its inherent characteristics allow it to act as both a structural and decorative architectural piece (FWPA, 2007).

The key features of glulam are its low variability in properties and the fact it can be manufactured into almost any length. It has comparable strength to steel although it is much lighter, which makes it relatively easy to transport and work with on site (FWPA, 2007). One disadvantage of glulam and known as its Achilles' heel is its relatively low stiffness (Marcroft 1992). Research has been done in an attempt to address this issue and ideas such as using steel reinforcement bars in the glulam members as well as the use of glass fibre reinforcement have been thought up as ways to make the members stiffer.

Glulam can be used in both residential and non-residential buildings and has a wide variety of uses including, headers, beams, girders, columns and truss members (Lam, 2001). Glulam is known for its aesthetic attributes, which can be a deciding factor in its use in the construction industry. This is in contrast to LVL, which is typically only used for structural purposes and is not generally renowned for its aesthetic qualities. As glulam can be manufactured into curved shapes, it provides design consultants (architects, engineers) the opportunity to express their artistic ideas, whilst still gratifying relevant strength requirements in building codes (Lam, 2001).

4.2.2 Cross Laminated Timber (CLT)

Cross Laminated Timber (CLT) consists of sticks of timber laid perpendicular to each other and pressed with adhesive to form a large timber panel. Panels are typically produced with 3, 5 or 7 layers and in various thickness up to 500mm. Panels are generally supplied in widths of 3m and lengths of 16 – 20m (Frangi et al. 2009). CLT was originally developed in Switzerland in the mid 1970's. As a proprietary product during its inception it went through more than two decades of ''trial and innovation'' so that it wasn't until the 1990s that it started to gain acceptance and use throughout Europe (Perkins & McCloskey 2010). The first industrial sized CLT manufacturing facilities were introduced in Austria just over 10 years ago and, as use of CLT panels has continued to grow, more facilities have been constructed throughout Europe (Perkins & McClosky 2010). A number of tests have been carried out to determine the structural performance characteristics of CLT panels. Vessby et al. (2009) carried out experimental tests on CLT in Sweden and were able to show that CLT panels have a high degree of stiffness and strength. These high strength and stiffness attributes associated with CLT have meant that for buildings with a high number of window and door openings that would usually require a unique bracing solution in a timber frame house, CLT can act as a whole system and provide adequate bracing to associated wind loads. Vessby et al. (2009) concluded in their test findings that CLT panels joined using strong connections coupled with its high level of stiffness, particularly in wall panels, allow CLT elements to have a strong stabilising potential.

CLT panels have recently started to become increasingly popular in structural engineering and are one of the upcoming building materials in the timber construction sector in Europe (Sturzenbecher, Hofstetter & Eberhardsteiner 2010). Throughout Europe, particularly in Austria, Switzerland and the UK, CLT panels are beginning to be used more regularly as an alternative to steel and concrete (Perkins & McCloskey 2010). They are being utilised as both structural wall and floor systems in office, retail, industrial and residential buildings (Frangi et al. 2009). Two pioneering buildings that have in no small way helped bring CLT technology to the forefront are the Kingsdale School in London by de Rijke March Morgan Architects, and Stadthaus Apartments (Murray Grove), also in London, by Waugh Thistleton Architects (Gagnon & Pirvu 2011).

There is potential for CLT panels to be used in non-residential buildings as an alternative to steel and concrete – not since the introduction of platform frame construction to Japan in 1974 has there been such a unique and revolutionary product (Perkins & McClosky, 2010). Countries around the world that have vast timber resources have a great opportunity to manufacture CLT in the short and medium term (Perkins & McClosky, 2010). NZ with its vast timber resources and timber manufacturing expertise has the potential to develop CLT technology for domestic construction and export markets in the future (Quenneville & Morris 2007). CLT has begun to gain popularity and increased use on a number of medium and high-rise structures. Lend Lease, one of Australia's largest property developers, has recently built the tallest multi-storey residential apartment building in the world out of CLT in the City of Melbourne (Silverman 2010). Going forward there is a need for basic design parameters and reliable characteristic values for CLT design (Serrano & Enquist 2010). There is also great potential for EXPAN building systems to be used in conjunction with CLT to create hybrid solutions for commercial office buildings.

4.2.3 Laminated Veneer Lumber (LVL)

LVL is a composite timber material that is constructed from sheets of veneer which are laminated together with their grains orientated in the same direction. These veneers are peeled from logs at into 3mm thicknesses. During the manufacturing process the veneers are hot pressed together to create LVL billets (Wilson & Dancer 2005). The LVL billets are typically 1.2m wide and 12-13m long, being dimensions governed by common transport limitations. During World War II airplane propellers were constructed out of LVL, then from the 1970s LVL had a variety of uses as a construction material e.g. beams, headers and flanges for I joists. Due to their uniformity and high strength characteristics, LVL products were and continue to be used as scaffolding planks (Lam 2001).

LVL members are inherently stronger, straighter and more uniform than solid timber and have a lower embodied energy than alternative materials such as steel and concrete (Page 2006, Perez 2008, John et al. 2009 & 2011)

There are some limitations and issues with LVL members. Firstly, some concerns arise in regard to the resins used in the LVL members' manufacturing process and the potential impacts they could have on both the environment and humans. Secondly, there are issues with performance characteristics, namely its spanning capabilities, stiffness, durability and ability to withstand lateral loads (Bayne & Taylor 2006). In order to address these performance characteristic issues, EXPAN systems are being developed, where they fabricate LVL components into larger sections. EXPAN is covered in detail in the following section.

4.2.4 EXPAN

EXPAN are prefabricated timber structural systems that provide a cost and time efficient system for the non-residential construction market (Crews et al. 2010). Currently LVL is the key material input used for EXPAN systems, where the LVL components are fabricated into larger members that create EXPAN systems (e.g. box beams, columns, floor systems and so on). Glulam can also be utilised for beam and column members and going forward there is also potential to use CLT as a key component in flooring systems. These systems were developed through the research consortium called the Structural Timber Innovation Company (STIC). The consortium was set up to develop and commercialise new prefabricated timber structural systems for open-plan multi-storey timber buildings, large span timber roofs and timber concrete composite (TCC) floor systems. EXPAN is the proprietary name given to these systems developed by STIC and will be one of the main systems focused on in this thesis.

As part of STIC, the University of Canterbury in Christchurch, NZ is developing innovative Post-Tensioned (PT) timber technologies utilising LVL. This innovative post-tensioning system for timber systems is patented as EXPAN and improves a timber building's seismic performance in comparison to the traditional steel dowel or nailed connection timber construction (Palermo et al. 2005a). Australia isn't typically a seismic region so earthquake and seismic performance of buildings isn't a major concern. EXPAN offers architects and structural engineers the ability to design large open plan buildings – research to date has predominantly focused on moment-resisting frames for resisting lateral and or gravity loads. One of the major benefits of EXPAN is that a number of strong, whilst ductile moment-resisting connections can be made. The EXPAN technology could be useful in multi-storey office buildings in Australia for post and beam construction as it has the potential to create longer spans with smaller beam sizes, with up to 50% less timber than solid LVL sections (Palermo et al. 2010).

The idea for EXPAN was conceived and adapted from post-tensioned precast concrete systems (Priestly et al. 1999). It was initially developed for seismic resisting frames and walls (Palermo et al. 2006). Moment resisting connections are created through the use of continuous unbonded post-tensioning cables, anchored at exterior columns, clamp beams and columns together. Experimental results demonstrated the system has an excellent seismic response (Newcombe, Pampanin & Buchanan 2010a). Design guidelines for seismic design of post-tensioned timber frames, based on procedures for precast concrete systems have been suggested by (Newcombe, Pampanin & Buchanan 2010b). The design procedure is based on displacement based design and provides design formulae for the main contributions to interstorey drift; beam and column rotation, joint panel shear deformation and connection rotation.

Past experimental testing on small scale post-tensioned beam-column connections showed that compression perpendicular to the grain in the column at the connection interface limited the connection moment capacity (Palermo et al. 2005b). The compression due to the post-tensioning force combined with the compression due to the connection moment created large localised stresses. The strength of LVL perpendicular to grain is about 25% of the strength parallel to grain, and the stiffness only 5%. This issue was more apparent in full scale testing by Iqbal, Pampanin & Buchanan (2010), where a significant reduction in stiffness and post-tensioning forces were observed. A 30mm thick steel plate at the connection interface was introduced and eliminated both problems. Long, fully threaded screws inserted as column reinforcement provided a reduction in post-tensioning losses but did not affect the reduction in stiffness.

Recent research has also focused on the gravity design of post-tensioned timber beams by Palermo et al. (2010). Continuous, unbonded and draped post-tensioning cables can be used inside timber box beams. The draped profile creates an uplift force in the beam at the locations of internal deviators, which helps to limit deflections and increase the load carrying capacity of the beam. The next step in the evolution of these systems is to investigate the performance of post-tensioned timber frames under gravity loading. The performance of the beam-column connection is an essential part of the design of these frames. In the design of these frames it is assumed that the lateral loads are resisted by walls, bracing or other lateral load resisting systems.

4.3 Timber and engineered timber use in the construction industry

4.3.1 Residential construction in Australia

The residential market is a large market segment in the Australian construction industry with revenues of nearly $30 billion over 2011/12 (IBISworld 2011b). Table 4-1 outlines the value of the different market segments in the residential construction market in Australia. Single detached housing makes up the largest proportion of total construction spend equalling close to $23 billion. Prefabricated timber manufacturers have been reliant on this market as their main source of revenue. In recent years this has posed an issue due to wide cyclical fluctuations in housing investment, as highlighted in Table 4-2. This has also corresponded with unfavourable trends in affordability, through escalating interest rates. Over the last five to six years in order to offset fluctuations in the housing market large-scale players (e.g. Australand) have increasingly expanded into contracting and property development activities in multi-storey apartments and medium density retirement homes. Other house builders (e.g. BGC) have even diversified into construction materials manufacturing (IBISworld 2011b). Similarly to builders that have been reliant on class 1 residential construction, manufacturers that develop EWP and prefabricated timber should be looking at other markets in order to diversify and not remain reliant on the volatile residential housing market.

Table 4-1 Residential construction market in Australia

Market segment	**2011-12 $Billion**	**2011-2012 % of total revenue**
New single-unit housing	22.7	75
Apartments & townhouses	2.3	7.5
Alterations, additions & repairs to existing dwellings	4.5	15
Speculative property sales	0.8	2.5
Total	$30.3 billion	100

Source: (IBISworld 2011b)

Table 4-2 New housing starts in Australia (2006 – 2012)

Year	**Single-unit housing (units)**	**% growth**	**Total housing (units)**	**% growth**
2006-07	106,538	2.2	152,177	-0.1
2007-08	107,269	0.7	158,536	4.2
2008-09	91,952	-14.3	131,680	-16.9
2009-10	112,141	22.0	165,540	25.7
2010-11	98,000	-12.6	156,500	-5.5
2011-12	97,000	1.0	148,000	-5.4

Source: (IBISworld 2011b)

Approximately 85% to 90% of newly constructed houses in Australia have outer walls made predominantly of brick (two-thirds of which are brick veneer), while just 5% to 6% of new housing is constructed with predominantly timber (IBISworld 2011b). The bulk of flooring installed in new housing is constructed using concrete (80% to 85%), with the balance constructed using timber (IBISworld 2011b). Structural softwood is primarily used for internal structural framing in residential construction and traditionally EWP, specifically LVL, has been used as bearers, joists, lintels, rafters and so on. Multi-unit apartment and townhouses have total industry revenues of $13.3 billion (2011/12). The purchase of material inputs into this type of construction (e.g. timber, steel, concrete products, glass products, and consumables) accounts for 20% of annual industry revenue, which amounts to $2.7 billion (IBISworld 2011b). Of these material costs, structural (wall and floor) costs are typically around 25% of material costs, so for prefabricated timber systems there is a potential market value of $675 million.

4.3.2 Non-residential construction in Australia

Non-residential buildings in Australia, in particular multi-storey commercial office buildings, are traditionally constructed with concrete and steel. These systems have proved to be successful solutions and are readily available, although these traditional forms of construction have inherent sustainability and environmental issues such as high-embodied energy and use of natural resources (John et al. 2011). These traditional forms of construction are responsible for a number of defects and, due to the inherent high levels of labour on-site, have helped to propagate the low productivity that is characteristic of the construction industry. Prefabricated timber structural systems offer a sustainable alternative to the traditional forms of construction (Page 2006, Perez 2008, John et al. 2009 & 2011). Being lightweight and modular in nature means they have potential to allow rapid installation on-site, which helps improve productivity (Bayne & Taylor 2006). There is limited use of EWP in structural application in multi-story non-residential buildings. Glulam and LVL on their own are limited in spanning capabilities though when fabricated into EXPAN systems have greater potential. After reviewing the literature, no buildings have been found to use EXPAN in the commercial construction market in Australia. It has had more success in the NZ market, albeit still minor with only 7 buildings adopting this system to date. Fabrication was a key issue for these buildings and will be discussed in further detail later in this thesis.

Table 4-3 Non-residential construction market in Australia

Market segment	2011/12 $Billion	2011/12 % Of total revenue
Office	4.8	30.4
Retail	4.5	28.2
Warehouses	1.9	12.1
Entertainment & recreation facilities	1.8	11.5
Factories	0.9	5.6
Other	1.9	12.2
Total	$15.8 billion	100

Source: (IBISWorld 2011a)

4.3.3 Potential market size for prefabricated structural systems in non-residential construction

In the commercial construction market in Australia total industry revenue in 2011/12 was $15.8 billion (Table 4-3). Material inputs account for 17.5% of industry revenue, which equates to $2.8 billion (IBISWorld 2011a*).* In commercial construction due to the increased complexity in building designs, consultant fees associated with design costs are significantly higher, as are fabrication and erection costs compared to residential housing. Structural costs for multi-storey non-residential structures are significantly greater than for residential structures, i.e. one commercial project will be the equivalent (in $ terms) to a large number of smaller residential projects. As shown in Table 4-4 structural costs are typically around 20% of overall material costs in non-residential construction. So, overall, this equates to a potential market of $550 million for prefabricated timber systems, which highlights a large potential market for organisations involved in the production of prefabricated timber systems.

Table 4-4 Structural costs as a % of overall structural costs

Project	Total construction costs	Structural cost	% Of overall construction costs
Educational building Nelson, NZ	$5.35m	$1.1m	21%
5 storey office building Wollongong, Australia	$17.70m	$3.7m	20%
Educational building, Sydney, Australia	$47.5m	$14m	29%
Educational building, Sydney, Australia	$62m	$8m	13%
33 storey commercial office tower, Sydney, Australia	$196m	$50m	25%
10 storey commercial office building, Sydney, Australia	$330m	$51m	15%
		Average	21%

4.4 Opportunities and benefits of using prefabricated timber construction in non-residential construction

Structural systems in the non-residential construction market have traditionally been dominated by concrete and steel. This is due to commercial buildings, in particular office building, requiring longer spans and timber traditionally being limited to low-rise, 5 – 6m spans (Bayne & Taylor 2006). With the introduction of CLT from Europe, timber and the development of EXPAN systems timber is now starting to have potential to compete with traditional forms of construction in the non-residential market. A number of societal changes are also beginning to indirectly support the use of timber in non-residential construction. Demand for high-rise Central Business District (CBD) office spaces has reduced due to the decrease in employment in insurance and financial services. As a follow on from lower demand for high-rise office space over the past decade, there has been a decentralisation of employment away from the CBD to the inner precincts i.e. Homebush near Sydney (IBISWorld 2011a*)*. This means an increase in low to medium rise buildings being constructed which in turn results in more opportunities for prefabricated timber systems.

Following on from the above, another factor helping support the use of timber structural systems in non-residential construction is the increasing demand for sustainable construction methods. LCAs' conducted on different building types have provided unequivocal evidence that timber structural systems lead to a more environmentally friendly building design. Table 4-5 compares results from a number of different studies. Aesthetic and character appeal are other positive aspects of timber. In Table 4-5 it also highlights when different LCA databases are used i.e. Alcorn and GaBi when conducting an LCA study on the same building achieved different results for total CO2 t/m^2 & GJ/m^2.

Table 4-5 LCA results from studies comparing timber (LVL), concrete and steel buildings

Type	Size (m^2)	Storeys	Structure	Total CO2 t/m^2	Total GJ/m^2	LCA Database	Reference
University Bldg	3536	6	Timber (LVL)	0.27	3.28	GaBi	John et al. 2009
University Bldg	3536	6	Steel	0.47	5.08	GaBi	John et al. 2009
University Bldg	3536	6	Concrete	0.45	3.89	GaBi	John et al. 2009
University Bldg	3536	6	Timber (LVL)	0.05	4.61	Alcorn	Perez 2008
University Bldg	3536	6	Steel	0.37	7.30	Alcorn	Perez 2008
University Bldg	3536	6	Concrete	0.32	4.90	Alcorn	Perez 2008
Out-patient	1640	1	Timber (LVL)	0.06	2.24	-	Page 2006
Out-patient	1640	1	Steel	0.11	2.75	-	Page 2006
Out-patient	1640	1	Concrete	0.16	3.10	-	Page 2006
Gym	680	1	Timber (LVL)	0.06	1.84	-	Page 2006
Gym	680	1	Steel	0.06	1.95	-	Page 2006
Gym	680	1	Concrete	0.12	3.05	-	Page 2006

Bayne & Taylor (2006) showed that some specifiers believed timber was important and could be enjoyed where there was a link to community spirit, 'human growth and development'. It is important to highlight that environmental benefits on their own merit won't persuade designers to specify timber as an alternative viable option to steel or concrete. For timber to be a truly competitive option in non-residential construction, the key performance drivers of time, cost, quality, availability and so on need to be addressed. These key drivers as well as a number of other issues are still present for timber structural solutions, and will be discussed in the following section.

4.5 Key issues limiting prefabricated timber systems in non-residential buildings

A number of studies have been conducted throughout Canada, USA, Australia and NZ highlighting potential opportunities and limitations of using prefabricated timber systems in non-residential construction. The common theme amongst all of these studies is that there is a notable absence of timber in non-residential construction (Bayne & Taylor 2006; Goetzl & McKeever 1999; McKeever & Adair 1995; Nolan 1994; Nolan 2010; O'Connor et al. 2004). The studies also point out that designers, namely architects and structural engineers, do not feel comfortable in designing large timber buildings. This lack of confidence in using timber amongst designers stems from a multitude of issues such as lead times, cost implications, connection details, availability, commercial risk, lack of assistance, inadequate training in timber design and poor marketing (Bayne & Taylor 2006). The following review analyses the literature and highlights the key issues limiting the use of prefabricated timber systems in non-residential construction in Australia and other parts of the world.

4.5.1 Codes - Building Regulations

O’Connor et al. (2004) outlined amongst designers, building codes are one of the largest issues in regard to timber use in non-residential construction. Goetzl & McKeever (1999) outlined how building codes limit timber use by 50% in non-residential construction in the USA. Codes seemed to be more limiting for timber in North America than in Australia, as the USA did not have performance based design options like Australia and were more restricted to prescriptive codes. O’Connor et al. (2004) reported that a number of designers had a perception that building codes were more restrictive then they actually are. Nolan (2010) surveyed building users and producers in Australia and findings of the study outlined that building code requirements were seen as being the greatest hindrance to timber’s use. Nolan’s result supports O’Connor’s finding, highlighting that from the period of 2004 to 2010 attitudes of designers haven't changed much.

Holmes, Crews & Ding (2011) investigated the influence that building codes and fire regulations have on multi-storey timber construction in Australia. The study looked at the impact of the Building Code of Australia (BCA) on two building case studies, an 8-storey timber commercial building and an 8-storey timber residential building. Results showed that currently under the BCA, through a performance based building design, prefabricated timber systems could be used in buildings to be constructed essentially to any height. This is provided that the design meets the necessary Alternate Solution performance requirements and is then signed off and given the go ahead by the Fire Brigade and the Building Certifier. Table 4-6 outlines a number of possible areas of the BCA where timber does not meet the Deemed-to-Satisfy requirements and the development of Alternate Solutions is a costly exercise. Section C – fire resistance is one of the biggest limitations, particularly for buildings over 4 storeys in height. Further issues and comments from each of the performance requirements are listed below in Table 4-6.

Table 4-6 BCA Alternate Solutions for case study buildings

BCA Performance Requirement	Issues	Comment
Section C – Fire Resistance		
CP1 CP2 CP4 CP6	Fire ratings of timber elements as typically non combustible materials (concrete and masonry) are to be used in fire rated elements	In Australia to date there has been no buildings constructed over 4 storeys though testing performed in Europe is comparable and could be utilised as evidence.
Section D – Access & Egress		
DP5	Typically non combustible materials must be utilised in fire isolated exits	Fire stairs in Australia are typically constructed in concrete, it's rare for anyone to use any other material

Part F1 – Damp and Weatherproofing		
FP1.4	Waterproofing of roof and external walls with materials not meeting deemed to satisfy provisions	There are currently no Deemed-to-Satisfy provisions for external walls
Part F5 – Sound Transmission and Insulation		
FP5.1 FP5.2 FP5.3	Acoustic separation doesn't meet tables/tested in BCA.	For timber there are limited acceptable forms of construction for floors and walls.
Section J – Energy Efficiency		
JP1	CLT has not been tested to meet Australian Standards / meet tables.	Becoming more common for new and innovative products to be used and tests performed in Europe are comparable.

Source: (Holmes, Crews & Ding 2011).

In order to address these issues, strategies such as CodeMark certification and proposals to change the BCA are potential options to help make building code approval easier for prefabricated timber systems (Holmes, Crews & Ding 2011).

CodeMark Certification

The Australian Building Codes Board (ABCB) in consultation with the New Zealand Department of Building and Housing (DBH), State & Territory governments, industry groups and prospective certification bodies set up the CodeMark certification scheme. It is a third party scheme developed to support the use of new and innovative building products, through the use of an internationally recognised process in which products can be assessed for compliance with the requirements of the building codes of Australia and New Zealand. The certification allows a product to essentially gain approval under Deemed-to-Satisfy provisions of the BCA, which through the issue of a certificate of conformity is able to provide confidence and certainty to regulatory authorities and also the market. In order to obtain CodeMark certification an organisation must apply through a certification product such as SAI Global, Global-Mark Pty Ltd and CertMark Australasia. Essentially any organisation can obtain approval provided it is able to demonstrate that its particular product meets the relevant requirements set out in the CodeMark Scheme Rules.

In regard to timber use as structural elements in multi-storey buildings, CodeMark certification has the ability to help reduce costs and time associated with such projects across a range of performance requirements (Holmes, Crews & Ding 2011). For example, if a certificate of conformity is achieved for a timber system in relation to fire performance requirements, it would then negate the need for a fire engineer to develop an alternate solution on future buildings, which is a costly and time consuming process. The issue at present is that there are relatively high costs involved to achieve CodeMark certification (circa $50,000 to $100,000) (Holmes, Crews & Ding 2011) and in relation to timber it would most probably need to be the manufacturer who is responsible for this investment; keeping in mind that manufacturers aren't going to spend the time and money to achieve certification if it isn't going to result in an increased demand for their products/systems.

(Nolan 2010) produced survey results that design consultants see building regulation requirements as one of the key factors that hinders the use of timber in class 2 – 9 buildings. In turn CodeMark certification could be a good avenue to provide an easier way to achieve BCA compliance in multi-storey timber buildings, though unless designers show an interest and increased use of timber in 4 storey plus buildings, timber manufacturers aren't necessarily going to invest the money into CodeMark certification. Another important thing to note is that compliance certificates are only valid for 3 years and then they have to go through the certification process again (Holmes, Crews & Ding 2011).

Change to BCA Legislation

The ABCB has a process in place called 'Proposals for Change' (PFC), which allows technical proposals the opportunity to change the BCA. In order to maintain appropriate thoroughness and consistency the Council of Australian Governments' regulatory principles are used. If a proposal is considered to have merit the Building Code Committee (BCC) may recommend that the proposal be included in the next draft for public review. If the BCC considers the proposal as being complex in nature, it may suggest that further research, analysis and consultation is performed. Proposing to change the BCA to be more receptive to timber's use in multi-storey buildings was considered by one of the building consultants interviewed as being a medium to long-term goal, whereas CodeMark certification is more short-term objective (Holmes, Crews & Ding 2011).

4.5.2 Difficult to design

A study conducted by Nolan (1994) found that in 1987 designers, namely architects and engineers, conducted most of the work in their careers on non-residential projects, but hardly any of this work was done using prefabricated timber systems. Only 3% of engineering in non-residential projects was done in timber and, of the architects interviewed by Nolan none were involved with the design of timber commercial buildings. Bayne and Taylor (2006) commented that it is not known whether the situation has improved in Australia over the last 30 years, though from their experiences they believed that very few designers are using timber in non-residential construction in Australia. There have been very limited examples of multi-storey timber buildings in Australia engineers and architects don't have much experience or precedence to go by.

Bayne & Taylor (2006) highlighted that timber manufacturers seemed to show a lack of understanding of how the whole construction process worked. The lack of standard connection details was also seen as a key reason engineers preferred to use steel in non-residential construction - as it was much easier for them (Bayne & Taylor 2006). Engineers saw working with timber as a frustrating process and Australian universities have limited emphasis on timber engineering. Many structural engineers commented in Bayne & Taylor's (2006) study that they had little to no experience in engineering with timber.

4.5.3 Costs

Costs are one the key factors when choosing particular structural systems on a construction project. There has been relatively limited literature on what the issues are that affect the costs of prefabricated timber systems. O'Connor et al. (2004) and Bayne & Taylor (2006) both highlighted that engineers found it took longer to design in timber, which results in higher design costs. In both North America and Australia there seemed to be a lack of generic design support information such as design data, span tables, standard connections and so on (Bayne & Taylor 2006; O'Connor et al. 2004). This in turn meant engineers have to design timber buildings from first principles, which would take time and as a result their design fees would be higher.

After a thorough review of the literature it became apparent that there have been limited economic studies of prefabricated timber systems used in buildings in Australia and NZ. Studies to date have primarily been based on virtual building designs using hypothetical rates (Page 2006; Smith 2008; Wong 2010; Mendez 2010 & John et al. 2011). Bayne & Taylor (2006) highlighted that quantity surveyors (QS) have limited experience with the costing of prefabricated timber systems. Typically the QS will add contingencies onto the costs to account for potential risks associated with lack of knowledge and robust costing data.

Table 4-7 outlines the construction costs of prefabricated timber systems compared to traditional forms of construction in a number of building case studies. Costs are broken down to a $/m2 rate. This helps provide a more transparent comparison between the studies. It is important to note that the case studies were conducted in different countries and in different years so it is difficult to make accurate comparisons for a number of reasons:

- Different currency values
- Different completion year of case studies
- Price of material inputs
- Price of labour and plant

Total construction costs of different building designs are a typical governing factor for choosing one particular system over another. Equally important to overall construction costs is certainty of costs. This is particularly important to building contractors in lump sum tenders and in guaranteed maximum price arrangements where they bear the risks if total costs go over this price – and in which the supply chain typically has a large role to play.

Table 4-7 Construction costs associated with different multi-storey building types in NZ

Type	Size (m2)	Storeys	Structure	Total $/m2	Dollar Year & Location	Reference
University Bldg	3,536	6	Timber (LVL)	2,834	2008 (NZ$)	Smith 2008
University Bldg	3,536	6	Steel	2,650	2008 (NZ$)	Smith 2008
University Bldg	3,536	6	Concrete	2,668	2008 (NZ$)	Smith 2008
University Bldg	3,536	6	Timber (LVL)	2,834	2010 (NZ$)	Wong 2010*
University Bldg	3,536	6	Steel	2,739	2010 (NZ$)	Wong 2010*
University Bldg	3,536	6	Concrete	2,702	2010 (NZ$)	Wong 2010*
Hotel	2,100	5	Timber (LVL)	632	2010 (NZ$)	Menendez Amigo 2010
Hotel	2,100	5	Concrete	585	2010 (NZ$)	Menendez Amigo 2010
University Bldg (NMIT)	1,980	3	Timber (LVL)	2,703	2011 (NZ$)	John et al. 2011
University Bldg (NMIT)	1,980	3	Steel	2,596	2011 (NZ$)	John et al. 2011
University Bldg (NMIT)	1,980	3	Concrete	2,689	2011 (NZ$)	John et al. 2011

* Wong (2010) completed a revised costing of a redesign of Smith's (2008) design.

There are a number of areas that affect prices of building case studies. For the purpose of this review a few of the key areas that result in different rates in the case studies are outlined below:

- For the timber designs, the rate used for a TCC floor system had an impact on the overall costs, where Smith (2008) estimated the floor system to be \$160m^3, Wong (2010) used \$265m^3 and Menendez Amigo (2010) used a rate of \$245m^3. Over a whole building these rates can have a substantial impact on costs.
- The rates used in LVL fabrication are an ongoing issue that needs to be addressed. Predominately hypothetical rates are used due to limited available data on built rates. Smith (2008) estimated \$200m^3 to \$500m^3 for fabrication, whereas Wong (2010) fabrication costs were closer to \$1000m^3.
- Smith (2008) used a smaller overall cost for the timber option in comparison to the concrete and steel options. Wong (2010) had a higher rate for the foundations due to thicker shear walls, he argued this rate was conservative and typically foundation costs for the timber option (due to lighter weight) should be less than concrete and steel buildings.
- The three studies failed to address or point out the different costs associated with the potential increase in costs of fire engineering services required for a timber building to obtain code approval.
- There was a common theme amongst all studies that the timber structural system (walls, floors and frames) was more expensive than concrete and steel options. The exception was Wong (2010) who estimated the steel structural system to be significantly more expensive than the timber option.
- Wong (2010) used the same building as Smith (2008), though the structural design was optimised and revised in Wong (2010). Through developing an optimised structural solution, Wong (2010) estimated a 1.8% saving.
- Preliminaries and margins ranged from 13 – 15% of overall costs between studies, which also had an impact on estimates between them.
- Overall the biggest issue with the studies (excluding John et al. 2011) is that they were all based on virtual building designs and hypothetical rates. In the present writers' opinion a more accurate database of 'as built' rates of timber structure systems in Australia and NZ is urgently needed.

- The issue with the cost analysis for NMIT building (John et al. 2011) is that is it based on the cost estimates devised by a Christchurch based quantity surveyor.

4.5.4 Performance issues

There was a negative perception of timber's performance capabilities amongst engineers. O'Connor et al. (2004) discovered that engineers were mainly concerned with timber's spanning capabilities, stiffness and durability issues and its ability to withstand lateral loads. Bayne & Taylors' (2006) study highlighted long-term deflection and creep as an issue amongst engineers. In Australia specifiers also believed they didn't have access to information in regard to the durability and deflection performance of the different timbers.

Participants in Bayne & Taylor's (2006) study believed that timber manufacturers seemed to show a lack of understanding of how the whole construction process worked, and that there were issues with connection details, in particular, how timber connected to other materials. The lack of standard connection details with timber systems was seen as a key reason engineers preferred to use steel in non-residential construction, as it was much easier for them. Some engineers saw working with timber as a frustrating process (Bayne & Taylor 2006).

4.5.5 Lack of skilled fabricators

There was a common theme amongst studies by (O'Connor et al. 2004, Bayne & Taylor 2006, Smith 2008 and Nolan 2009) that there is a lack of fabrication capacity in Australia. This lack of skilled workers affects engineers' confidence in using timber, as they generally feel much more confident that with the large number of steel fabricators out there, they are confident the project will be a success if done in steel. This issue of fabrication capabilities is a huge constructability issue. The lack of skilled fabricators in the Australian industry has a detrimental impact on supply capacity, which for a large multi-storey building if materials aren't supplied on time will lead to problems with the construction program and lead to time and cost issues on the project, and which will no doubt put construction contractors off the idea of using timber. Smith (2008) undertook research into the feasibility of a 6-storey prestressed timber building in Christchurch, New Zealand. He discovered the importance of the fabrication process and found there is a major gap in the production process. There is also an issue in regard to the costs of the fabrication process, where there were substantial differences in quotes for the cost of fabrication from $200 to $500 per m^3.

Crews et al. (2010) outlined that even though there are issues with estimating fabrication costs, the bigger issue is that LVL producers don't possess the required equipment to fabricate members efficiently in terms of time and costs. Smith (2008 pg. 113) summarized the point by stating: ''this gap in the supply of the system (timber) must be addressed in order for the method of construction to become truly viable''. The fabrication issue will be addressed in greater detail in the supply chain section of the report. It's important to note that in Australia and New Zealand there are currently *no* CLT manufacturers and there are relatively few LVL manufacturers/fabricators that are capable of supplying a multi-storey (4-storeys plus) timber building to a competitive cost and time. Dunn & Forsythe (2009) prepared a report for the FWPA entitled ''Strategy for large span second storey timber and wood products'' and they suggested that the best vehicle for implementing an increase in long span timber beams ''is via the frame and truss manufacturers as they are well positioned to create engineered timber solutions customized to suit individual project needs''.

4.5.6 Environmental issues

Even though there are inherent environmental benefits in using prefabricated timber systems (as shown in Table 4-5), a number of authors believe wood can actually be detrimental to the environment. Imhoff (2001) edited a book entitled '*Building with vision: Optimising and finding alternatives to wood*'. The book focused on the negative aspects of wood and outlined that wood wasn't as environmentally friendly as people thought. Several times it stated that deforestation was occurring more rapidly due to logging and that harvesting of old growth forests was occurring in order to build wood framed houses. Provided softwood inputs come from sustainable plantation forests, deforestation shouldn't be too much of a concern. Government policy will play a role in this going forward.

Eamus et al. (2009) believe that the planting of large new forest plantations can lead to a number of detrimental environmental impacts, particularly in Australia. They outline that planting a lot of trees in one area can deplete groundwater reserves and increase soil salinity. Also historically low recharge rates of the aquifer has also contributed to low water table. These low recharge rates have been brought about by a decade long drought in the region. As a result of these impacts in Perth, Australia the residents have had to resort to desalination plants as one alternative to obtaining fresh water as large tree plantations have significantly lowered the water table, making it hard to pump water from the ground. These desalination plants are highly energy intensive and create a number of environmental issues themselves (i.e. CO_2 emissions). Monitoring of new plantations and ensuring density in new plantations isn't too high can help alleviate this issue going forward.

4.6 Recommendations and initiatives outlined in literature

As detailed above, a large number of issues need to be addressed in order for wood to be a competitive and viable option for use in multi-storey and non-residential construction. A number of authors have come up with their own promotional initiatives and recommendations that they believe will help address the various issues and concerns that are associated with wood use in non-residential construction (Nolan, 2010; Bayne & Taylor, 2006; O'Connor et al, 2004; & McKeever & Adair, 1998). Nolan (2010) recommended that the timber industry take steps to develop its own capacity in timber design and construction, and that to be successful as an industry they need to be willing to support and help building design professions and the building industry in general. In recent times there has been a trend for major timber producers to withdraw from close interaction with the construction market (Nolan 2010).

While this practice may simplify their business models, it can result in lost opportunities, industrial political and the impacts of competitors. Increasing interaction with end users is one of the key recommendations to implement that was echoed across a number of studies (Bayne & Taylor 2006; Nolan 2010).

After reviewing the literature, a number of potential benefits of using prefabricated timber systems are clear i.e. environmental, aesthetics, Occupational Health & Safety (OHS.) A number of issues in Australia prevent the use of prefabricated structural solutions, of all of the issues highlighted in the literature the capacity of the supply chain is the most critical factor that relates to a number of other highlighted issues i.e. cost, fragmentation, time etc. and so on (Bayne & Taylor 2006; Smith 2008). There is a large gap in the literature as to how this issue should be addressed. Having the necessary manufacturing and fabrication capacity to produce prefabricated timber structural systems at a competitive price in a reliable time frame and to a predetermined quality is of critical importance to their successful implementation in the non-residential construction market.

As shown in Figure 1.1 upstream from the design and manufacturing stages in the supply chain is raw material acquisition (logs) and, potentially, sawmilling – depending on the prefabricated timber system. These stages (log supply and sawmilling) are outside the scope of this research as detailed in 1.6 Research Scope and Focus. This decision was made because the logs are used for a number of different products i.e. pulp and paper, structural sawn timber, non-structural applications such as weatherboards. The resulting upstream supply chain is different for each of the aforementioned products – albeit logging (and milling) is an important stage that can affect time and cost of prefabricated timber systems and the organisations involved are focused towards supplying commodity products with little regard to move further upstream and value add the product. As this research is focused on the finished value added prefabricated product, this stage is not addressed in the model development. There is still value covering these areas and the issues relevant to this stage will be covered in the following section.

4.7 Raw material acquisition (forestry/log supply)

Davidson & Hanna (2004) explained that softwood timbers, particularly coniferous species, are cheap and easy to process and are the primary product used in the production of EWP in Australia. As coniferous trees are the main material input into EWP, their supply will in turn influence the potential output for the EWP industry. Radiata Pine is the key softwood timber used in EWP in Australia and NZ. For LVL whole softwood logs are supplied to the manufacturing plant, where they are debarked and the logs veneered into 2-3mm sheets which are then used to make LVL billets. For CLT, softwood logs are sent to a sawmill where they are machined into lengths of softwood timber at varying dimensions and strengths. Then these lengths of timber are manufactured into CLT. This supply of softwood logs is a significant component of the overall material costs with some 70% of costs of CLT attributed to the softwood lumber input (Gagnon & Pirvu 2011).

Forestry and raw materials acquisition is an important element, particularly in the long term, ensuring logs are sourced from sustainable plantation forests. 'The availability of softwood (coniferous) log supplies – that is, the standing volume of timber that is potentially harvestable – has largely determined the quantity of Engineered wood products (EWP) produced in Australia' (Davidson & Hanna 2004). Plantation softwood availability in Australia is expected to plateau soon with the estimated growth of softwood log supplies in Australia at around only 0.5% per year for the next forty years (Davidson & Hanna 2004). Thomson & Kelly (2007) highlighted that there's been a decrease in investment in softwood plantations meaning there will only be minor increases in stock over the next 10 – 20 years. Gavran et al. (2012) prepared a report under ABARES, using data collected by the National Plantation Inventory Program – which includes detailed data from plantation owners and managers. Their findings outlined in Figure 4.1 support the aforementioned authors' highlighting that the supply of softwood logs used in prefabricated timber systems is going to stay flat for the next 40 years.

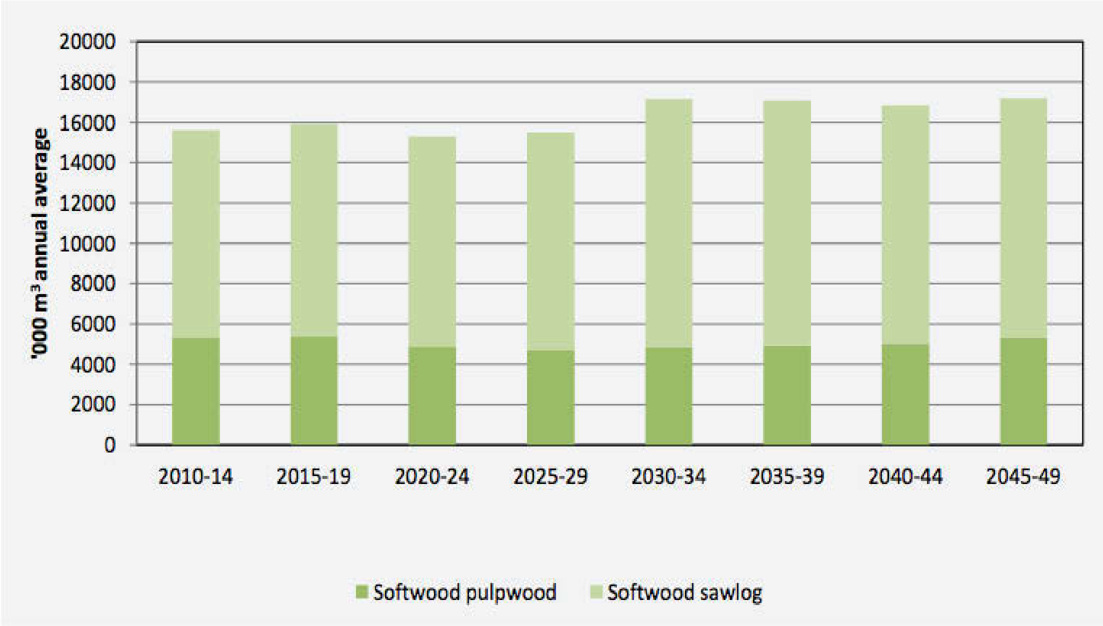

Figure 4.1 Australia Softwood Timber Harvest Forecast 2010 - 2049

Source: ABARES 2012 (Gavran et al. 2012)

As depicted in Figure 4.2 the supply of softwood logs is also going to plateau over the period of 2012 – 2040.

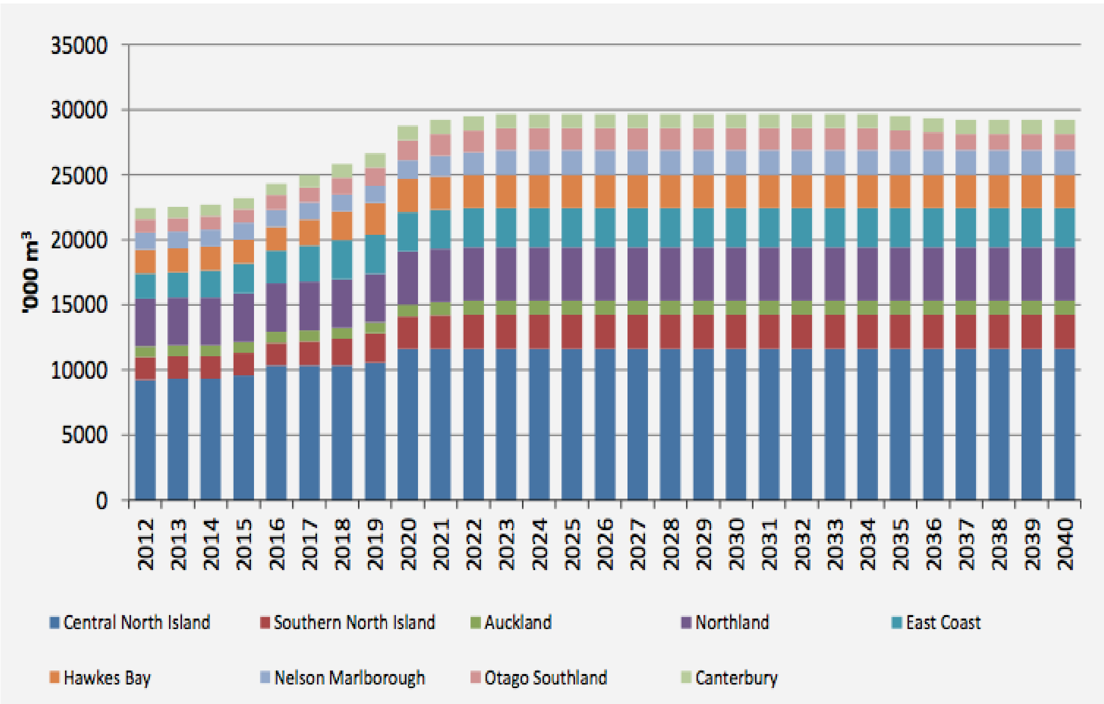

Figure 4.2 New Zealand Softwood Timber Harvest Forecast 2012-2040

Source: (Shelton 2012)

‘‘In the light of these expectations of moderate supply and capacity increases, the challenge for Australia’s EWP manufacturers is to remain competitive in world markets that are characterised by declining real prices’’ (Davidson & Hanna 2004, pg. iii).

This plateau of softwood log supply isn’t so much of an issue in the short term, more so in the medium to long term. Australia's population at 30 June 2012 of 22.7 million is projected to increase to between 36.8 million and 48.3 million in 2061, and reach between 42.4 million and 70.1 million in 2101 (ABS 2013). As demand for prefabricated timber systems increases, adequate supply of softwood logs will pose an issue, in particular for CLT, which uses a lot of softwood timber inputs. Coupled with a projected lack in supply and a potential increase in demand locally, there’s also the impact of demand from other regions. The growth of China and India indicates that their demand for softwood resources will outstrip their local supply. The Chinese government forecasts demand for softwood in China will rise to 350 million cubic metres by 2015, with 150 million cubic metres coming from imports (Shelton 2012). EWP have an inherently higher recovery yield compared to sawn timber, and this coupled with their more efficient use in structural designs would seem EWP to be the logical direction forward in extending the utilisation of softwood resources.

4.8 Conclusion

This chapter provided a review and analysis of prefabricated timber systems. It established there is potential for prefabricated timber systems to be a sustainable alternative to traditional forms of construction in the non-residential market. It was established that prefabricated timber systems are predominantly used in residential construction, where they are used as a commodity product. The literature also highlighted a number of key issues that are limiting the use of prefabricated timber systems in non-residential construction both in Australia and other parts of the world. A gap in that literature was highlighted around how the supply chain of prefabricated timber systems impacts on the time, cost and quality of the systems and in turn their commercial viability. In particular there was a lack of knowledge in relation to how the organisations along the supply chain impact on the performance of the systems. Supply chain management has been established as a way to help improve the supply chain and performance of prefabricated timber systems.

Chapter 5 Research Method

5.1 Introduction

This PhD research aims to understand 'how' the supply chain influences the performance (time, cost and quality) of prefabricated timber systems and what can be done to improve the performance of these systems. In particular, it examines how the structure of the organisations along the supply chain affects performance of prefabricated timber systems. This work contributes to the study of ETO supply chain research, by applying structural contingency theory to the ETO supply chain and testing the theory in relation to prefabricated timber systems. This research has been undertaken in two parts – with the first part consisting of two rounds of data collection and the second part used for testing the model/theory. The first round is a case study focusing on establishing the key performance issues along the supply chain of prefabricated timber systems in Australia, NZ and Europe. The second round of interviews focuses on 'how' the organisations along the supply chain are structured and the particular services they offered as well as 'why' they were set up in this way. A link is then established in relation to how these different organisational structures lead to time, cost and quality issues along the supply chain of prefabricated timber systems. A cross case analysis of the issues between the regions is also undertaken. *Semi-structured* i*nterviews* were the prime data collection method in this part of the research.

This chapter covers the methodology selected as the best fit for achieving my research goals. The research methodology used in this thesis is predominantly qualitative in nature. This chapter will outline the selection and application of the case study methodology and why it is the most applicable to this research. This chapter will address the various forms of data collection used including interviews, documentation and personal observation. The data analysis methods and framework used for testing structural contingency theory in relation to organisations along the supply chain for prefabricated timber systems is also covered.

5.2 Research Method

A number of different research methods could be used to achieve the aims and objectives of this research. The type chosen is reliant on a number of different factors, including the researcher's preconceptions and experience (Taylor & Bogdan 1998). Yin (2009) outlines five different types of research strategies:

- Experiment
- Survey
- Archival analysis
- History
- Case study

Each of these different research strategies has a specific focus: *experiments* are events where the researcher has the ability to directly influence behaviour in a systematic manner; *survey* is a strategy that's appropriate when the research is focused on describing the incidence or prevalence of a phenomenon; *archival analysis* relies on archival records as a data source; *history* is where the researcher obtains data from primary or secondary documents; and finally *case study* is of a contemporary set of events. Yin (2009) outlines that when deciding, which research strategy to adopt a number of things have to be addressed including the form of research question, how much control the researcher has over the events, and whether the research is focused on contemporary or historical events.

Table 5-1 Relevant Situations 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)

This research consists primarily of 'how' and 'why' type questions. These we covered in 1.1.5 Research aims and objectives. Using Table 5-1 above, three different research methodologies could be used for these types of questions including *Experiment*, *History* and *Case Study*. This research is focused on practical issues in the construction industry that are contemporary events; so according to Table 5-1, *History* is not a relevant methodology for this research. No control over behavioural events is required nor the ability to directly influence behaviour, so the *Experiment* methodology isn't suitable for this research. Therefore *Case Study* was selected as it is the most suitable methodology, as this research focuses on 'how' and 'why' types of questions, on contemporary events and does not require control over behavioural events. A case study is defined as 'an empirical inquiry that investigates a contemporary phenomenon within its real-life context…you would use a case study method because you deliberately wanted to cover contextual conditions - being that they might be highly pertinent to your phenomenon of study' (Yin 2009 p. 13).

A number of studies have used the case study methodology to research the supply chain in the construction industry. Cox & Townsend (1998) undertook case study research on six organisations in the construction industry in their seminal text *Strategic Procurement in Construction: Towards better practice in the management of construction supply chains.* Olsson (2000) undertook qualitative case study research on supply chain management of the Swedish housing industry. Lambert, Pugh & Cooper (1998) used empirical case studies to develop a generic map for the supply chain structure of an organisation. Arbulu & Tommelein (2002) undertook case studies to analyse the different supply chain configurations of ETO pipe supports. These studies support and demonstrate that case studies have been shown to be an appropriate methodology to study supply chains.

The focus of this research is on the ETO supply chain of prefabricated timber systems. A number of authors have studied ETO products from a supply chain perspective including structural steel (Tommelein & Weissenberger 1999), precast concrete (Sacks, Akinci & Ergen 2003), HVAC ductwork (Holzemer, Tommelein & Lin 2000), concrete elements and facades (Vrijhoef & Koskela 2000), transformers (Tommelein, Walsh & Hershauer 2003) and power distribution equipment (Elfving 2003). These studies have predominantly focused on time issues along the supply chain and identification of possible improvements. A gap was highlighted in the literature around issues along the supply chain that effect performance (time, cost and quality) of ETO products. There was also a severe lack of literature on the study of the supply chain of prefabricated timber systems. The study objective in this research is on the supply chain of prefabricated timber systems, in particular the innovative EXPAN system. These products are contemporary in nature, and have only been used in NZ and Australia for the past couple of years. This research is predominantly qualitative in nature and for the reasons discussed in the following section.

5.3 Qualitative vs. Quantitative Research

It is traditionally accepted that quantitative research examines data, which are numbers, and qualitative research examines data, which are narrative (Easterby-Smith, Thorpe & Lowe 1991). In general quantitative researchers support a positivist paradigm and qualitative research supports a relativist paradigm (Hyde 2000). Qualitative research methods describe characteristics of people and events without comparing events in terms of measurements or amounts. They are designed to give real and stimulating meaning to a phenomenon by involving the researcher directly or indirectly in the process. Data collected in qualitative research typically includes observations, interviews and actual participation by the researcher (Taylor 2000). Using case studies, this thesis will utilise these forms of data collection (interviews, direct observations and documentation). According to Taylor (2000), parts of this thesis will necessarily be qualitative in nature. Even though this research will, predominately, be qualitative in nature, there will be some aspects which utilise quantitative data.

Quantitative methods concentrate on measurements and numbers or quantities of characteristics displayed by people and events (Thomas 2003). Parts of this research, such as costing and program documentation from building case studies, will be quantitative in nature. The majority of data in this research, however, is qualitative in nature, including *semi-structured interviews, documentation* and *direct observation.* The following sections outline in more detail these forms of data collection and why they were used in this research.

This research also adopts a deductive research approach or top down approach. Hypothesis testing methodology was adopted under this deductive approach, where a known theory is used, then a hypothesis is established and observations are found to then either confirm or disconfirm the theory. A deductive approach was used in preference to a inductive, theory building approach primarily due to research being qualitative. Hyde (2000) outlined that concepts associated with quantitative method typically adopt a deductive approach with statistical numerical analysis being predominant. This research on the contrary is primarily qualitative with narrative description and constant comparison used as analytical techniques. With this in mind an deductive hypothesis testing methodology is more appropriate than a theory building bottom up inductive approach.

5.4 Case studies - prefabricated timber supply chains in Australia/NZ and Europe

5.4.1 Research Design

The case studies consist of two rounds of data collection. The first round is a case study focusing on the key performance (time, cost and quality) issues along the supply chain of prefabricated timber systems in Australia, NZ and Europe. A cross case analysis of the issues between the regions is also undertaken. The second round focuses on 'how' the organisations along the supply chain in Australia, NZ and Europe are structured and the particular services they offered as well as 'why' they were set up in this way. *Semi-structured interviews* were the prime data collection method in this part of the research.

In the round one case study, semi-structured interviews were undertaken with industry practitioners along the supply chain of prefabricated timber systems. Participants outlined their role and experience working with prefabricated timber systems. Then the predetermined interview questions were asked/answered with the opportunity to diverge into other areas of relevance. Each interview lasted between one and two hours. Respondents who had experience working directly on projects that utilised prefabricated timber systems provided some rich data on the various issues that occurred along the supply chain.

The results from the round one case study highlighted that the structure and services of the organisations along the supply chain have a large impact on the performance of prefabricated timber systems. A second round case study was undertaken focusing specifically on the ETO companies involved in the manufacturing, fabrication, design and installation of prefabricated timber systems. Similar to round one, the round two case study used semi-structured interviews as the predominant form of data collection, and this was done to achieve more data specifically around the organisations and the services they offer. Obtaining more information on the services offered by organisations is important as they have the potential to impact the performance of prefabricated timber systems. Interviews were undertaken with senior managers from a number of organisations in Australia, NZ and Europe. Examples of semi-structured interview questions are available in **Appendix D – Example of semi-structured** interview questions R1 Australia/NZ and **Appendix E – Example of semi-structured** interview questions R2 Australia/NZ.

Gibson (2009) outlined that a potential issue with the use of semi-structured interviews is that the interviewer will have to make judgements 'in the heat of the moment' about what is relevant and what flow of conversation is to follow. To address this concern the focus on the round two interviews was to gain a rich understanding of the size, locations, services offered, experience and so on of the organisations as opposed to how they directly impact the cost, time and quality of prefabricated systems.

5.4.2 Data collection method

Chapter four highlights a number of issues along the supply chain for prefabricated timber systems (e.g. manufacturing and fabrication capacity, lack of design expertise, lack of installation capacity). When considering the data collection method for part one of the research, case studies were undertaken to compare the issues highlighted in the literature analysed in chapter four. Interviews were chosen to be the most suitable technique for this case study. Interviews are a great way to gain understanding, as they have the ability to allow interviewees to freely respond and outline their views on a particular issue (Silverman 2010). Walsham (2002) describes interviews as a valuable primary data source, which allow researchers to gain access to different interpretations of participants towards actions and events.

There are potential concerns with undertaking interviews. One is that when interviews are too tightly controlled there is opportunity for richness in data to be lost – particularly expressions of interviewees' views. Conversely, if the interviewer is too passive, there is potential to lose the opportunity of exploring new directions and obtaining feedback outside the prescribed questions

(Walsham 2002). To address these concerns interviews were set up in a semi-structured manner, where a number of questions were used as a guide whilst still allowing the opportunity for discussion to move away from the questions and gain further insights. All interviews were conducted by myself – this ensured a level of consistency and maintained a level of control over the interviews. It also allowed me to gain an increased understanding of issues as interviews progressed. As new issues were highlighted by interview respondents, I was able bring them up in subsequent interviews and see if they were recurring themes or specific to that particular individual.

Interviews can be enhanced if they are undertaken in the interviewee's place of work (Wood 1997). Preece, Sharp & Rogers (2002) outline if people are interviewed in their own work or home setting, they may find it easier to talk about their activities. To help assist with the integrity of data collected, the majority of interviews were undertaken face-to-face at the interviewee's workplace. Some interviews were conducted over the phone or through Skype due to geographical constraints. All the face-to-face interviews were transcribed and notes were also made on any revealing facial expressions or comments. All the interviews conducted over the phone or Skype were digitally recorded and transcriptions were then made of the recordings. It was particularly important to digitally record and transcribe interviews over the phone, as this allowed me to re-listen and transcribe the interview later. This also enabled me to pick up nuances in the interviewee's voice that would have been difficult to do so during the original interview. Consent for digitally recording interviews was obtained from interviewees.

Ethics Approval was obtained from the UTS Research Office and as part of the requirements confidentiality was maintained throughout the interviews. To ensure this, names of interviewees were desensitised. All interviewees were informed their name would be desensitised and I believe this helped achieve a richer data source by facilitating a greater freedom of expression during the interviews. Each interviewee signed a consent authority form; for those interviews undertaken over the phone a consent form was emailed to them and they signed it, and returned it by fax or email. An example of the interview consent form is available in **Appendix A – Interview consent authority** form.

As aforementioned the aims of the interviews were to gain insights from experienced industry practitioners on the various issues along the supply chain for prefabricated timber systems.

The overall focus of these interviews was aimed at extracting the following information:

Round 1 case study interviews

- Assessing the complexity of the supply chain – namely, what are the various stages in the supply chain for prefabricated timber systems
- Identifying what are key issues along the supply chain that affect the performance (time, cost and quality) of these systems

Round 2 case study interviews

- Identifying the organisations involved in the production of these systems and which is responsible for each process
- Identifying the differences between issues and organisations in Australia and NZ and Europe

The case study interviews were undertaken in a semi-structured manner. Gibson (2009) outlined that a key feature of semi-structured interviews is that they allow the interviewer to consider predetermined themes for an interview whilst still providing the flexibility of participants to highlight and diverge onto other themes or topics that may be relevant. A number of authors have used semi-structured interviews to study the supply chain including, notably Dainty, Briscoe & Millett (2001) who undertook research into the barriers of supply chain integration between subcontractors and main contractors. Hines (1996) also used semi-structured interviews to develop a network sourcing model and document supplier coordination and development as critical causation factors within network sourcing. Er (2010) outlined the advantage of using semi-structured interviews, as a form of data collection in that it allows for changes in direction, where unanticipated areas can be brought to the fore, whilst still offering the opportunity to address the predetermined themes and questions.

5.4.3 Sampling

The expert sampling method was used to derive an initial sample for the interview from an Internet search. The search highlighted timber industry bodies in Australia and NZ and five key personnel from these bodies were interviewed first. Undertaking interviews with a number of prominent figures from industry bodies that had vast experience, knowledge and contacts amongst those experienced in prefabricated timber systems was a great way to begin the interviews. Then the snowball sampling method was used as a method to assemble further potential interviewees. It was used because each interview allowed me to obtain further key contacts from practitioners in the industry. Patton (1990) outlines that snowball sampling is utilised to discover a wide sample of persons through people who know other people within the area under examination.

One advantage of snowball sampling within a particular field is that known as referrals. After meeting with initial subjects who match the target research criteria based on their knowledge and experience in the field, a number of contacts were obtained as referrals (Beardsworth & Keil 1992). This helped ensure that the people I interviewed were experts in the field of prefabricated timber systems and that rich data could be collected. Snowball sampling was a great way to increase the level of comfort between the interviewee and me, as through being introduced by a common personal contact, the subject seemed to be more willing to respond to interview questions in a detailed and candid manner. Even though most contacts obtained from subjects were receptive and willing to assist in the research, a number of people did not respond to my requests for an interview. A total of sixty-five (65) interviewees were contacted either by email or telephone and offered the opportunity to undertake an interview. Fifty-six (56) participants (Round 1 – 42 and Round 2 – 14) responded and agreed to undertake the interview, which equates to a response rate of 86%.

Boyatzis (1998) emphasised the importance of having some prior general knowledge in the industry you are studying by stating:

> Knowledge relevant to the arena being examined is crucial as a foundation, often referred to as tacit knowledge. For example, it is difficult to perceive and make sense of patterns in Shakespeare without understanding Greek and Roman mythology. Strauss & Corbin (1990) claimed that theoretically sensitivity is the ability of the researcher to recognize what is important, give it meaning and conceptualize the observations. In this sense, a researcher needs to have the patience to perceive themes or patterns and the 'lens' through which to view them. 'Cleaning your glasses helps, but conducting qualitative research involves emotional, value-laden, and theoretical preconceptions, preferences and worldview's (Boyatzis, 1998, pp.7-8).

5.4.4 Selection of interviewees

The initial selection of subjects for Round 1 interviews was based on the following criteria:

1. Industry practitioners with experience working with prefabricated timber systems in all aspects detailed in point below.
2. An even spread of participants across the entire supply chain for prefabricated timber systems including manufacturing, fabrication, design and detailing, installation. Having a good spread of participants across the entire supply chain was important in order to obtain a good understanding of all the issues that effect time, cost and quality of the systems.

As mentioned earlier, following on from interviews in the round one case study, a second round case study was undertaken focusing solely on the organisations responsible for the delivery of engineered-to-order prefabricated timber systems (i.e. manufacturing and fabrication). Organisations were sourced from a combination of round 1 interview data as well as an internet search. Senior managers from these organisations were interviewed and these organisations were chosen based on the following criteria:

1. Organisations focused primarily on the delivery of prefabricated timber systems to the market
2. Organisations that were involved and had experience in the non-residential construction market
3. A mix of organisations from the Australasian and European markets

5.4.5 Data Analysis

Two well-used analytical approaches towards qualitative research are known as top-down and bottom-up. Top-down makes use of a theory to interpret data, as opposed to bottom-up, which is a grounded approach in which the data informs the themes of research (Gibson 2009). A combination of a top-down and bottom-up approach was used. Firstly, a bottom-up approach was used in the round one case study to identify the themes and key issues of the research. Structural contingency theory was then used as an interpretive tool for the round two case studies and, later in the thesis, will be used in more detail through the building case studies to assist the understanding of how the organisations involved in delivery of prefabricated timber systems impact on the time, cost and quality of those systems.

The transcribed data was analysed with the assistance of NVivo 9. NVivo 9 was developed by QSR (Qualitative Solutions and Research Pty Ltd) and is a computer aided, qualitative data analysis software package that enables the efficient storage of primary data. It also assists in coding, sorting and organising the text. Individual interview documents were uploaded into a project file in

NVivo 9. Interviews that were face-to-face were transcribed during the interview on paper and then later in Microsoft Word. A transcription was also undertaken of the interviews that were undertaken over the phone and were digitally recorded. These transcriptions were undertaken on NVivo 9 as it allows you to play and then replay audio files section by section - this helps facilitate transcribing the audio files to text. An example of a transcribed interview is available in **Appendix C – Interview transcript example** – R1 Australia/NZ.

Interviews were then subjected to a thematic analysis as described above. The interpretive themes, as well as those identified through an open coding process, were sorted and labelled in the text as nodes in the NVivo 9 program. Following Bazeley (2007), text in the uploaded documents was categorised by highlighting relevant phrases and assigning them to a node or common theme. Additional themes were added as required. Following this process, nodes can be collated and displayed in reports. A sample report from NVivo 9 is available in **Appendix B – NVivo 9 node** report. This Node summary was used in the development of Table 6-2.

5.5 Case studies – Prefabricated timber systems used in non-residential buildings in Australia and NZ (building and testing projects)

5.5.1 Research design

Three building case studies were undertaken to analyse supply chain issues established in the part one case studies. The building case studies were then used to test structural contingency theory in relation to the supply chain of prefabricated timber systems. Pattern matching was used to analyse the case study data (interviews, documentation, personal observations etc.) and in turn to test structural contingency theory (Campbell 1975). Three building case studies were studied and individually analysed with the pattern matching technique. Yin

(2009) expounded that using multiple case studies provides you with a better chance of doing a good case study. Single case studies are vulnerable in that you limit your findings and conclusions to only one case study. Theory testing was performed individually on each of the three case studies. The robustness of the theoretical statement cannot be drawn on the basis of just one test, but only after a series of tests. Therefore, using multiple case studies provides better analytic results as you have the opportunity to compare and potentially draw cross-case conclusions.

The prefabricated timber systems focused on in the building case studies in this research are EXPAN systems. EXPAN is an ETO product and was chosen as the focus of this research because, prior to the development of these systems, there were limited prefabricated timber structural systems available to be used in the multi-storey non-residential construction market in Australian and NZ. CLT and other prefabricated timber structural systems were looked into though it was established there weren't enough building case studies available in Australia and NZ. It was found that there was only one multi-storey residential project in Australia using CLT and no multi-storey non-residential projects using CLT. Due to this lack of case studies it wasn't feasible to focus on CLT.

EXPAN prefabricated timber systems are a recent innovation to the construction industry in Australia and NZ; there are still limited building case studies available using these systems. To date there have been seven buildings that have adopted EXPAN technology, which are outlined below.

1. Nelson Marlborough Institute of Technology, Nelson, NZ
2. Massey University College of Creative Arts building, Wellington, NZ
3. STIC office – University of Canterbury, Christchurch, NZ
4. TUMU ITM Building, Napier, NZ
5. BRANZ Nikau building, Wellington, NZ
6. MOTAT Aviation Display Hall in Auckland, NZ
7. Carterton District Council Events Centre, North Island, NZ

This list of projects was established from interview feedback in part one of the research and also through an internet search. Moreover, a number of projects that are planning to use EXPAN are currently in the design stage, but as the construction of these projects hasn't commenced yet, they are not suitable to be used as case studies for this research, though once these projects have been completed they could offer an area for future research.

5.5.2 Selection of building case studies

The selection of building case studies was based on the following criteria:

1. Multi-storey non-residential construction utilising EXPAN technology for the structural system
2. Buildings constructed in Australia or NZ

Following the selection criteria the following projects were selected to be studied in detail in this thesis:

- Nelson Marlborough Institute of Technology (NMIT), Nelson, NZ
- STIC office at the University of Canterbury, Christchurch, NZ
- University of Technology, Sydney (UTS) floor systems

NMIT and the STIC office were chosen out of the list of seven completed projects because they were the only multi-storey non-residential buildings; the other projects were only single storey (aside from Massey, though limited data was able to be obtained from the project – so it was unusable for the purposes of this research). To the author's understanding, no completed buildings in Australia have utilised EXPAN technology though as part of the research testing at the University of Technology, Sydney, a number of prefabricated timber systems were used for testing. Even though no actual buildings have been constructed, the supply chain of these test specimens was studied as the third case study.

The overall focus of these case studies was aimed at extracting the following information:

- Assessing the complexity of the supply chain – Identifying what are key issues along the supply chain that affect the performance (time, cost and quality) of these systems
- Identifying how the structure of supply chains and organisations along it affects the performance (time, cost and quality) of prefabricated timber systems
- Testing structural contingency theory in relation to the supply chain and organisations involved in the production of prefabricated timber systems

5.5.3 Data Collection

It was envisaged that data from these case studies could be obtained to confirm issues established in the part one of this research and to also test structural contingency theory. The main forms of data collection in these case studies came from *interviews* with project participants, *documentation* and *direct observations*. In case studies there are typically six sources of evidence including *documentation, archival records, interviews, direct and participant observations* and *physical artefacts* (Yin 2009). Archival records weren't applicable to this research as it focused on contemporary events and, as I had no involvement in the projects, participation observation wasn't a feasible form of data collection. As the research was focused on establishing the key issues along the supply chain, physical artefacts weren't a relevant form of data collection either.

Semi-structured *interviews* were used to achieve data collection from the building case studies. Undertaking interviews with key project participants including project and construction managers allowed feedback on the key issues along the supply chain to be established. In particular obtaining key lessons learned from the project participants provided some rich data. Various forms of *documentation* were obtained from the building case studies including project control plan (PCP) reports, cost plans, construction programs as well as secondary data and documentation from a number of industry reports, particularly in the NMIT case study. Data from construction programs helped provide useful information around the issues along the supply chain that affect the time and delivery of prefabricated timber systems. Likewise cost plans and costing data helped highlight issues that impact on the costs. Undertaking interviews with project participants and discussing the issues established in the documentation from the projects helped highlight how the organisations and their structures impact and potentially cause these issues.

Yin (2009) pinpointed a number of strengths with the use of documentation as a source of evidence including the fact that relevant documents contain exact information and details from a project (i.e. cost plan and PCP reports) that can be viewed repeatedly and are stable as data sources. Some weaknesses with documentation as a form of evidence revolve around selectivity and reporting bias. In this research this was addressed by objectively sourcing and analysing data. *Direct observations* were also made during visits to sites, and to manufacturing and fabrication facilities, to establish any potential issues that could affect the performance (time, cost and quality) of prefabricated timber systems. These observations were made to help support findings from *interviews* and *documentation*. The *direct observations* also helped highlight issues in relation to quality.

5.5.4 Data Analysis

According to Yin (2009), the least well developed procedures in case study research are procedures for linking data to propositions, and criteria for interpreting such findings. There are five key analytical techniques for case studies: pattern matching, explanation building, time-series analysis, logic models and cross-case synthesis (Yin 2009). For case studies, pattern matching is one of the most desirable techniques to analyse case study data. Campbell (1975) demonstrated that pattern matching could be used to validate and test theories by linking data to propositions. Case study data is then gathered, and compared to the predictions of the theory (Hyde 2000). The other analytical techniques - explanation building, time-series analysis, logic models and cross-case synthesis - were considered though not seen as appropriate for this research.

Pattern matching involves comparing the two patterns (predicted from theory and actual from case study data) in order to establish whether they match or not. Pattern matching is a core procedure in qualitative theory testing of case studies – where observing a pattern of measured values with an expected pattern developed by a hypothesis can test theories (Yin 2009). If these patterns match, a hypothesis can be supported and likewise if the patterns don't match the hypothesis is not supported. Trochim (1989) outlined the importance of having a theoretical pattern of expected outcomes, and then through observing a pattern of effects an attempt can be to match the two (predicted and observed) and validate the theory. Hak & Dul (2009a) following on from Trochim (1989) observed that a key aspect of pattern matching is to ensure that the expected pattern and hypothesis are clearly specified before matching occurs.

Figure 5.1 depicts the basic pattern-matching model where theoretical ideas are used as a basis to develop a hypothesis and a predicted pattern based on the ideas of the theory. As aforementioned, ideas from structural contingency theory are applied to the supply chain and from this theory a theoretical pattern has been established where unless organisations along the supply chain are structured to suit the market needs and expectations of the environment, performance will be limited and issues will occur in relation to time, cost and quality. The building case studies are then used to develop an observed pattern and establish whether, when organisations and the supply chain aren't structured to suit the market needs and expectations of the environment, issues will occur in relation to time, cost and quality of the prefabricated timber systems.

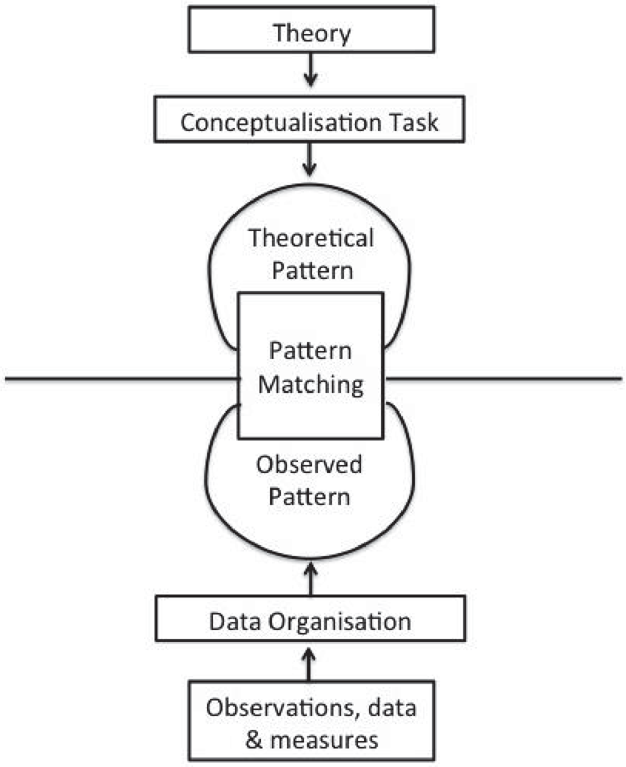

Figure 5.1 The basic pattern-matching model
Adapted from Trochim (1989)

5.5.5 Hypothesis/theory testing using case studies

Hak & Dul (2009b) reduced the methodology of theory testing from case studies to seven steps, which are depicted in Figure 5.2. The pattern matching technique is used throughout these seven steps and is discussed below. This research adopts these seven steps as a framework, where each of the three building case studies will individually follow these steps and test the structural contingency theory in relation to the supply chain for prefabricated timber systems.

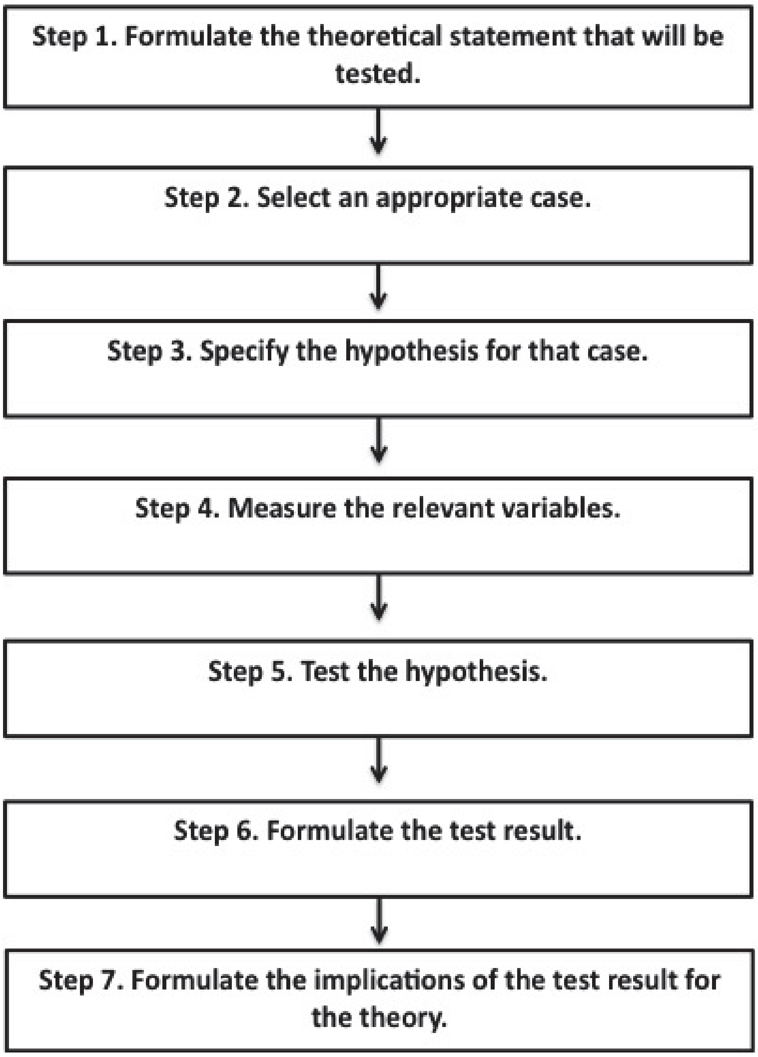

Figure 5.2 Seven steps to testing theories from case studies

Step 1. Formulate the theoretical statement that will be tested.

Structural contingency theory outlines there should be a fit between the organizational processes and the environment. Company business models (configurations) that match the environmental requirements should perform more successfully than those that don't (Burns & Stalker 1961; Lawrence & Lorsch 1967). When applying structural contingency theory to the supply chain, the individual dimensions of the chain should be aligned in order to achieve the best performance (Flynn, Huo & Zhao 2010). This means the entire supply chain or business network should be structured in such a way that they achieve an ideal fit to best suit the external environment.

Step 2. Select an appropriate case.

Cases were selected as dependent variable designs to test a sufficient condition proposition in a dependent variable design. Following on from section 5.5.2, case studies were selected 'where condition X is present in the case study and pattern matching is done to discover whether outcome Y is present in the observed pattern' (Hak and Dul 2009b p. 7). Condition X in this research is related to case studies where there is a lack of integration between organisations along the supply chain, and the supply chain isn't structured in a way that best meets the needs and expectations of the environment. Outcome Y is related to the issues that affect the performance (time, cost and quality) of prefabricated timber systems along the supply chain and are directly related to the organizational structure and lack of integration along the supply chain.

Step 3. Specify the hypothesis for that case.

As aforementioned, this thesis aims to test structural contingency theory when applied to the supply chain and ETO organisations involved in the production of prefabricated timber systems in Australia and NZ. The null hypothesis developed is – organisations involved in the production and delivery of prefabricated timber systems needs to change their structures to suit the non-residential environment and better meet the needs and expectations of customers in this market to improve the performance in relation to time, cost and quality. The expected pattern is that, when organisations and the supply chain as a whole aren't structured in a way that best meets the needs and expectations of the environment, issues along the supply chain will occur in relation to time, cost and quality. An alternate hypothesis was also developed where the organisations involved in the production and delivery of prefabricated timber systems does not need to change their structures to suit the non-residential environment and better meet the needs and expectations of customers in this market to improve performance in relation to time, cost and quality.

Step 4. Measure the relevant variables.

Criteria for valid and reliable measurement are the same for any type of research strategy, be it a survey, an experiment, a case study, or another theory-testing research strategy. In this research, case studies are used and data evidence is obtained through interviews, documentation and personal observations. Measurement entails determining whether X is present and whether Y is present. The result of this measurement is the ''observed pattern''.

Step 5. Test the hypothesis.

Testing consists of comparing the observed pattern with the expected pattern. In the present example, testing consists of determining whether when condition X is present pattern matching in the case consists of checking whether outcome Y is present in the observed pattern.

Step 6. Formulate the test result.

'The test result is either a *disconfirmation* of the hypothesis or a *confirmation*' (Hak and Dul 2009b p. 8). In this research, the hypothesis is disconfirmed if Y is absent in the dependent variable design. As aforementioned, outcome Y is related to the issues that affect the performance (time, cost and quality) of prefabricated timber systems along the supply chain directly related to the organizational structure and lack of integration along the supply chain.

Step 7. Formulate the implications of the test result for the theory.

'Conclusions about the robustness of a theoretical statement cannot be drawn on the basis of just one test, but only after a series of tests. Hence, discussing the implications of a test result always implies comparing the result with those of earlier tests in a series of replications' (Hak and Dul 2009b p. 8). In part two of this thesis, three building case studies are used to test structural contingency theory in relation to the supply chain for prefabricated timber products. It's important that each case individually tests the theory (Campbell 1975; Yin 2009). A discussion can then be undertaken to establish whether over these case studies the theory and hypothesis were either disconfirmed or confirmed.

5.6 Conclusion

This chapter reviews both quantitative and qualitative research and outlines the logical selection of the case study methodology to use in this research.

Qualitative case studies interpreted through the use of structural contingency theory are a suitable approach for research to model how the supply chain and organisations impact on the performance of prefabricated timber systems. The data collection process, including the selection of subjects, has been considered.

Following the research design outlined in this chapter, chapter six follows and reports on the findings and analysis from part one of the research outlined in Part One of Chapter 5. Chapter 7 will follow by developing a preliminary supply chain model based on the findings in part one in Chapter 6 as well as strategic procurement literature and structural contingency theory. Chapter eight then reports on the findings and analysis from building case studies. The building case studies in chapter eight are used to test structural contingency theory in relation to the supply chain for prefabricated timber systems.

Chapter 6 Data Collection & Analysis – Part one case study results

6.1 Introduction

This chapter presents the findings from part one of the research. Case studies were undertaken to find out key issues along the supply chain that affect the performance (time, cost and quality) of prefabricated timber systems. Interviews were the primary data collection tool, and were conducted with practitioners involved in the various stages of the supply chain for prefabricated timber systems. Interviews were conducted in Australia and NZ and also four countries in Europe. The first part of this chapter presents the findings from the interviews. Interviews were conducted in two rounds – forty-two (42) Round 1 interviews were undertaken to establish key issues that occur throughout the supply chain. Round 1 interviews also helped highlight the difference between the supply chain for prefabricated timer systems in residential and non-residential markets – in particular, in multi-storey construction. Interviews were also undertaken in both Australia and NZ and Europe. Europe has a more mature market for prefabricated timber systems and interviews were done in both regions to establish whether issues along the supply chain were similar.

Fourteen (14) Round 2 interviews were conducted. Similar to interviews in Round 1 they were conducted both in Australia and NZ and also throughout Europe. These interviews were undertaken specifically with the ETO companies responsible for the production (manufacture and fabrication) of prefabricated timber systems. Interviews were undertaken with senior leaders from these companies in order to gain a greater understanding of their business models, what processes they perform, and why. It was of particular interest to establish the differences in the company business models in Australia and NZ and then Europe.

Interviewees were limited to practitioners involved in the design stage and downstream to the construction site – manufacturing, fabrication, distribution, installation were all inclusive of this scope. Interviews were not undertaken with people from stages upstream from manufacturing (i.e. plantation/log supply and sawmilling for some prefabricated systems such as CLT and glulam). The reason interviewees were not undertaken with practitioners in these stages of the supply chain was because a significant amount of data is already available in the literature. The issues in these upstream stages have been addressed in the literature review in chapter 4.

Throughout this chapter, interview findings are a summary of the key themes from all interviewees. When specific reference is made to a certain interviewee their title and a number will refer them to the appendix. i.e. Architect 1, Consultant 1 etc. The final part of this chapter analyses the interview data in detail and a cross analysis is conducted between interview results in both Round 1 and Round 2. The differences in the markets in Australia, NZ and Europe are highlighted as well as the different organisational structures of ETO companies involved in the production of prefabricated timber systems in the different regions.

6.2 Round 1 Case Study

6.2.1 Australia/NZ

Interviews were undertaken with 28 industry practitioners from various stages of the supply chain of prefabricated timber systems in Australia and NZ at various times between June 2011 and July 2012. They represented the manufacturing stage upstream to the construction site and included manufacturers, distributors, engineers, architects, contractors and developers (details of interviewees in Table 6-1). A number of authors (Bayne & Taylor 2006; Nolan 2009) have outlined the various opportunities and constraints of using timber in non-residential construction in Australia and NZ. These studies have looked into general constraints and have used surveys and focus group sessions to establish findings. The aim of this case study was to focus specifically on the key issues across the supply chain that impact on time, cost and quality of prefabricated timber systems. Undertaking semi-structured interviews with industry practitioners allowed me to establish the different issues that occur between different markets, i.e. residential and non-residential.

Table 6-1 Round 1 Interviewee details – Australia/NZ

Interviewee	Company Type	Country	Work Experience
Architect 1	Architecture	NZ	15 - 20 years
Architect 2	Head Contractor	Australia	20 + years
Architect 3	Head Contractor	Australia	20 + years
Architect 4	Architecture	NZ	0 - 5 years
BCA Consultant 1	Head Contractor	Australia	20 + years
Business Development Manager 1	Manufacturing	Australia	20 + years
Business Development Manager 2	Manufacturing	Australia	20 + years
Client Representative 1	Client	NZ	20 + years
Construction Manager 1	Head Contractor	NZ	20 + years
Consultant 1	Consultancy	NZ	10 - 15 years
Consultant 2	Consultancy	Australia	20 + years
Consultant 3	Consultancy	Australia	5 - 10 years
Director 1	Manufacturing	Australia	20 + years
Director 2	Manufacturing	Australia	20 + years
Distributor 1	Distribution	Australia	20 + years
Fire Engineer 1	Engineering	Australia	10 - 15 years
Floor Manufacturer 1	Manufacturing	NZ	15 - 20 years
General Manager 1	Manufacturing	Australia	15 - 20 years
Installer 1	Sub-Contractor	Australia	20 + years
National Product Manager 1	Manufacturing	NZ	20 + years
Plant Manager 1	Manufacturing	NZ	20 + years
Plant Manager 2	Manufacturing	Australia	15 - 20 years
Project Manager 1	Head Contractor	NZ	20 + years
Project Manager 2	Head Contractor	Australia	10 - 15 years
Project Manager 3	Manufacturing	NZ	20 + years
Specialist Project Engineer 1	Head Contractor	Australia	20 + years
Structural Engineer 1	Engineering	Australia	20 + years
Structural Engineer 2	Engineering	NZ	0 - 5 years

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 and the key issues affecting performance (time, cost and quality) are listed in Table 6-2. A level of importance ranking is attributed to each of the issues listed. This is expressed as a percentage (%) and was determined by nodes established in the NVivo 9 report; the issues with the highest number of nodes were ranked and given a percentage (%) based on this ranking.

Table 6-2 Key theme affecting performance of prefabricated timber systems

Issues	Level of importance ranking (%)
Fabrication process	40%
Fragmentation between supply chain	25%
Building code requirements	12.5%
Design and detailing	10%
Installation capacity	7.5%
Logistics/ transportation between stages	5%

Fabrication process

For prefabricated timber systems used in non-residential construction the fabrication stage in the supply chain was highlighted by most interviewees as being a key issue. This stemmed from the fact that in Australia/NZ prefabricated timber systems have predominantly been used in the residential construction sector - in single and double storey detached housing. Prefabricated timber elements such LVL and glulam that are used in the residential market are Make-to-Stock (MTS) products, i.e. manufactured to standard sizes. There is very little value adding or fabrication work done to these products and they are essentially commodity products. Consultant 2 outlined, 'they are manufactured like a giant sausage factory … the manufacturer has little to no contact with the end customer and very little way of knowing exactly where the products are being used.' The supply chain for these products is outlined below in Figure 6.1.

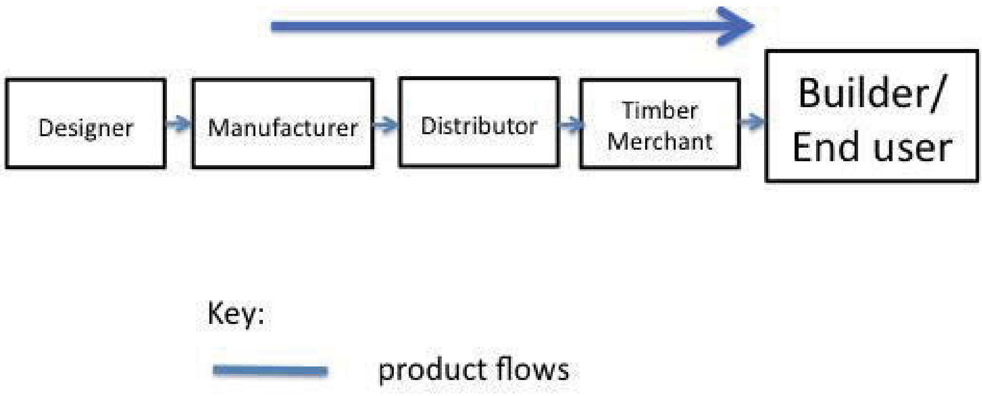

Figure 6.1 Supply for MTS prefabricated timber products used in residential market

An architect and engineer design elements in nearly all cases from a range of standard sizes. National Product Manager 1 outlined, 'there is very little fabrication or value adding performed after the manufacturing stage, though at each stage downstream from manufacturing (distributor and timber merchant) some 20 – 30% is added to material costs.' These costs are included even though no real value is added to the product. General Manager 1, from a manufacturing company, highlighted that this is a key issue and stated, 'In my opinion unless it is political everyone in the supply chain should add value.'

Non-residential buildings are typically larger and more complex than residential buildings. Prefabricated timber systems in turn need to be larger and more complex to cater for the larger spans and higher loads. This increased complexity in larger non-residential structures means fabrication is generally needed, which is a key process in the supply chain. The increase in complexity and unique nature of each project in the non-residential market means each system is individually designed for each project. This is a key change from the residential market and the product changes from a MTS product to an ETO product. A recurring theme amongst interviewees from all stages of the supply chain was that there is very little capacity in the fabrication stage. Table 6-2 outlines the supply chain for prefabricated timber systems that require fabrication into larger elements for use in the non-residential market. National Product Manager

1 outlined 'This lack of capacity (in fabrication) is market driven … we are aware this lack of capacity has a large impact on the cost and time of the systems though until there is an increase in market demand for the product it is difficult to change our operations or invest in the necessary capital to make it more efficient.' This has flow-on effects both upstream and downstream in the supply chain.

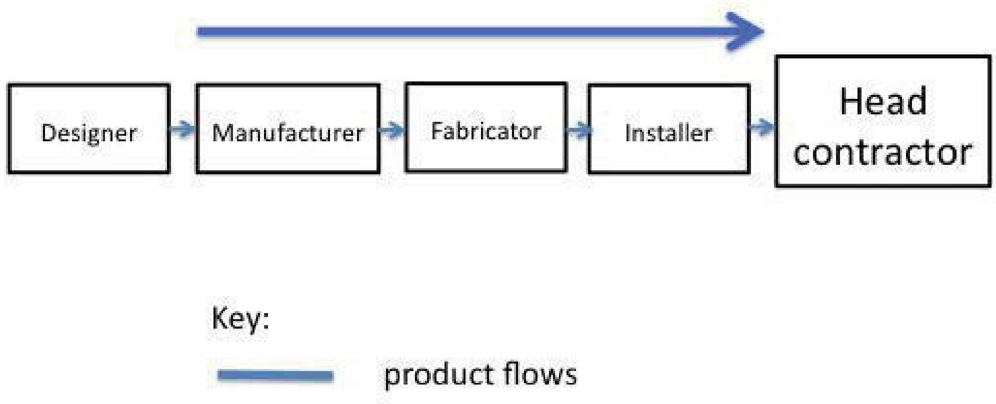

Figure 6.2 Supply for ETO prefabricated timber products used in non-residential market

Another key theme in conjunction with the limited capacity to produce systems cost and time efficiently was design capability - more importantly the integration and communication between design and fabrication. Consultant 3 outlined 'only one fabricator in the whole of Australia and NZ has expertise and the ability to successfully integrate design and fabrication. This helps to address quality concerns though they still have limited capacity, and time and cost issues are still prevalent.' From the NVivo 9 report a number of interviewees also highlighted that the quality of fabricated elements was an issue. This quality assurance was said to be a result of the high levels of manual labour needed during the fabrication process. The limited amount of automation meant that it was possible for people to make mistakes when fabricating elements.

Fragmentation between stages in supply chain

From the interview analysis 'fragmentation' and 'lack of communication' were also key themes that came up with multiple nodes on Nvivo9. This lack of communication between stages was highlighted as a key issue that affects time, cost and quality of prefabricated timber systems. As outlined earlier, not only is there a lack of fabrication capacity but a number of fabricators outlined the lack of communication they have with manufacturers when receiving components i.e. LVL to fabricate into prefabricated systems. Consultant 3 observed: 'there seems to be a lack of interest from the manufacturers to follow their products to the next process (downstream) … once it leaves their plant it seems like they aren't interested in providing any more support or follow up.'

Project manager 3 from a manufacturing/fabrication company outlined that on a number of projects the communication between themselves and the head contractors has been less than ideal. He argued that the head contractors don't give them enough lead time to fabricate elements in time – if they were engaged earlier on in the project lifecycle they would have more time to do front end work. For large timber projects, due to the lack of fabrication capacity and fragmentation, traditional procurement methods where design and construction are separate will cause problems, and it's important fabricators and even manufacturers on larger projects are brought in early on in the design stage not only to allow them plenty of front end lead time but also provide input into design.

Building codes

From the thematic analysis, building codes came up in large number of nodes. Building code approval for prefabricated timber elements was a particular issue - where it not only takes longer to achieve approval though it typically costs more as well. In Australia and NZ building codes aren't favourable to the use of combustible materials as structural elements in multi-storey non-residential construction. BCA Consultant 1 outlined that these limitations in the codes stem from the Great Fire of London in the late 1600s. Structural Engineer 1 highlighted that 'In Australia and NZ the prescriptive Deemed-to-satisfy requirements are very limiting … quite possibly the most conservative in the world … for large multi-storey non-residential buildings to be constructed in timber a performance based design will need to be developed.' The building code approval occurs during the design stage prior and sometimes in unison with the manufacturing/fabrication of elements. The current cost issues are associated with the extra engineering design fees and extra time associated with negotiations with building code authorities, certifiers and fire brigades. Fire Engineer 1 noted that 'some strategies to address these issues going forward in the short term are through Code Mark certification and in the medium to long-term proposals to change the building code of Australia. '

Design/detailing

The lack of design expertise in the industry as a whole was another recurring theme. Feedback from interviews outlined there few engineering and architectural firms in Australia and NZ have experience with prefabricated timber systems, and in general it took most engineers and architects longer to design them. This resulted in more cost and time during the design stage. Structural Engineers 1 & 2 outlined that this lack of experience stemmed from limited exposure during university as well as lack of experience designing systems on real life projects, both of which were due to a lack of demand for such systems. A number of fabricators did have specialist design and detailing expertise in-house, though this was of limited capacity, particularly in respect of the development of documentation and drawings on larger projects (4 or more storeys).

The fabricators that didn't have in-house design expertise highlighted that engineers and architects had a limited understanding of their capacity - particularly the cost associated with detailing members, as it is mostly done by hand and there is limited automation in the process. Shop drawings were another recurring theme that was brought up. They posed an issue as no party seemed to want to take responsibility for producing them. The fabricators and engineers explained that they weren't their responsibility and neither generally had the expertise or capacity to produce them.

Installation capacity

'Installation' was another key word/node that came up during the thematic analysis. Consultant 3: 'prefabricated timber may cost more in upfront structural costs compared to concrete and steel, though cost and time savings can be achieved in rapid installation due to its lightweight prefabricated nature … this has been demonstrated on a number of projects in Europe.' Construction Manager 1 outlined that it is critical that this installation capacity is addressed as, on a project he was involved in, they had issues during installation, which led to the project taking longer to construct when compared to a concrete alternative. There are also very limited specialist timber installers in Australia and NZ. This is demand driven, though one company has just started up (2012) and Installer 1 stated: 'I see the potential in these kind of lightweight systems in the future … there is a gap in the supply chain in this space so I've sent a number of people from my team over to the UK to work with and learn from an experienced company over there … they can then return with skills that can be used in the Australian market and to help ensure these systems can be installed efficiently to achieve time and cost savings.'

During the thematic analysis a number of nodes were identified in relation to Europe. A key recurring theme throughout interviews was that Europe had significantly more experience than Australia and NZ in the production of prefabricated timber systems. It was suggested by a number of interviewees that a lot could be learned from Europe and to do a comparison between the issues that occur along the supply chain there. Consultant 2: the 'Australian market is very similar in structure to the UK market … same issues, perceptions, etc … though they are still more advanced than us in regard to prefabricated timber … other parts of Europe i.e. Austria, Germany, Switzerland are on a another level in relation to sophistication and experience with prefabricated timber.' Following this feedback, it was decided to undertake interviews in Europe to see if issues along the supply chain are similar and what could be learned from their experiences.

Logistics/transportation between each stage

Interviewees highlighted that the lack of manufacturing and fabrication facilities around Australia and New Zealand resulted in potential supply chain issues from the manufacturing to fabrication and then from fabrication to the site. Project Manager 1 and 2 highlighted how 'on a few projects there has been delays in elements arriving to site … this is a serious issue and can affect the critical path of the project.' Director 1 from a manufacturing company explained that 'transportation companies don't typically like timber as it isn't stacked on gluts … it's harder and takes longer to load and unload elements on and off trucks.' Shipping elements from NZ to Australia involved relatively high amounts, leading Consultant 2 to highlight that this is due to a lack of competition among the container shipping companies in this region. There is a duopoly and as a result they can control prices and keep them inflated.

Quality is also a key issue during logistics and transportation. As timber swells and shrinks when wet it is critical that elements are kept dry during transportation. General Manager 1 from a fabrication company mentioned that 'when receiving materials from an upstream manufacturer a number of times they are affected by exposure to rain or sun … this is primarily due to inferior plastic wrapping they use to cover the materials during transportation. It is cheaper and of lesser quality then the plastic wrapping produced and used in the USA.'

6.2.2 Europe

Interviews were undertaken with 10 industry practitioners in Finland, Austria, Germany and the UK between August and September 2011. Details of interviewees are outlined in Table 6-3. This round of interviews came about from a recurring theme in Round 1 interviews in Australia and NZ, that many countries in Europe were well advanced in the design and delivery of prefabricated timber elements. Through establishing the key issues along the supply chain of prefabricated timber elements in a number of European countries and then comparing these issues to those present in the Australian & New Zealand, it was decide that much could be learned. A more detailed analysis between the two regions will be performed later in this chapter.

Table 6-3 Round 1 Interviewee details – Europe

Interviewee	Company Type	Country	Work Experience
Architect 5	Architecture	Austria	15 - 20 years
Architect 6	Architecture	Finland	20 + years
Consultant 4	Consultancy	UK	20 + years
Consultant 5	Consultancy	UK	20 + years
Consultant 6	Consultancy	UK	15 - 20 years
Consultant 7	Consultancy	Germany	15 - 20 years
Consultant 8	Consultancy	Germany	20 + years
Development Manager 1	Development	Austria	15 - 20 years
Development Manager 2	Development	UK	15 - 20 years
Professor 1	Academia/University	UK	20 + years
R&D & Innovation Director 1	Manufacturing	Finland	20 + years
Site Manager 1	Head Contractor	UK	20 + years
Structural Engineer 3	Engineering	UK	15 - 20 years
Structural Engineer 4	Engineering	UK	20 + years

As detailed in Table 6-3, interviews were undertaken with practitioners from the various stages of the supply chain including designers (engineers and architects), manufacturers/fabricators, and contractors/project managers. Similar to Round 1 interviews in Australia and NZ, the scope of interviews was limited to stages from manufacturing downstream to the construction site. A number of key themes were established through a thematic analysis performed with the aid of NVivo 9. The use of nodes in NVivo 9 helped establish these themes from the interview transcripts. 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 and the key issues affecting performance (time, cost and quality) are listed in Table 6-4 below. A level of importance ranking is attributed to each of the issues listed. This is expressed as a percentage (%) and was determined by nodes established in the NVivo 9 report; the issues with the highest number of nodes were ranked and given a percentage (%) based on this ranking.

Table 6-4 Key theme affecting performance of prefabricated timber systems

Issues	Level of importance ranking (%)
Up and downstream communication along the supply chain	35%
Weather and transportation/logistics throughout Europe	25%
Building codes	25%
Fires on construction sites	15%

Up and downstream communication along the supply chain

Communication between structural engineers and manufacturers/fabricators is typically not an issue. This is because they are generally part of the same company or there is some kind of partnership/alliance in place. The issue that arises on occasion is the communication between the head contractor, architect and the timber contractor. In Europe in most cases the timber contractor is responsible for design, detailing, manufacturing/fabrication and installation. Structural Engineer 3 highlighted this: 'in prefabricated systems such as CLT it is imperative to get penetrations sorted out during the design stage and NOT on-site … the minimal amount of work on site the better … where a penetration is needed it is better to route out a larger opening during manufacturing.'

Another issue highlighted is when a contractor has altered or added additional penetrations to elements on-site, and the structural engineer has to come out and inspect the openings to ensure this doesn't affect the structural integrity of the elements. This holds up the project and can lead to time and cost issues. So it's imperative there is good communication between the architect, head contractor and timber contractor from very early on in the project - to ensure design integration. Site Manager 1 and Development Manager 2 highlighted the importance of early engagement/communication between timber contractors and head contractors, particularly for larger projects. This will help mitigate any lead-time issues and allow input from the timber contractor at all stages of the supply chain.

Weather and transportation/logistics throughout Europe

During the thematic analysis a number of nodes were identified around logistics/transportation. After looking over interview transcripts in more detail it became apparent that the supply of materials from the manufacturing facility to the project site was a potential issue to cost, time and quality. In Europe the majority of prefabricated timber elements are manufactured in Germany, Austria and Switzerland. They are then transported across to other regions of Europe including the UK. Development Manager 1: 'In my experience the optimal logistics/transportation route is through loading elements onto trucks in the manufacturing facility and then shipping by the trucks directly to site … elements are then unloaded onto the project just-in-time … though this is a perfect scenario and a number of things can occur i.e. elements get wet during transportation, manufacturing is delayed, ships are delayed, materials on trucks aren't delivered in the right sequence etc.' Structural Engineer 4 also noted that 'on a number of projects members have got wet or damaged during transportation … this has affected the quality of the members and the engineer has had to go out and inspect the members prior to installation.' These issues all impact on the time, cost and quality.

Building codes

In the thematic analysis building codes were another recurring theme. The biggest issue with building codes in Europe was that they change from country to country. Consultants 4 – 8 are affiliated with a timber industry development association in the UK and they outlined that some countries are more accommodating than others to prefabricated timber systems being used as structural elements. The UK building codes are still relatively limiting when it comes to using timber in larger multi-storey buildings. Prescriptive code requirements are also limiting in a number of other countries and this results in higher costs and time associated with engineers having to develop performance based solutions.

Fire on construction sites

During the thematic analysis a number of nodes were established around the words ‘fire’ and ‘construction site’. Prefabricated timber elements being combustible in nature means they are more susceptible to fire during construction than concrete and steel buildings. Consultant 4: ‘In the UK there has been a number of cases of fires occurring during the construction stage of large timber buildings … these fires have catastrophic effects on the project.’ Not only are they primarily a safety concern to people working on the project and others in the near vicinity though they also have a large effect on time, cost and quality. Depending on the severity of the fire, it will no doubt lead to a complete knock down and rebuild to the area where the fire occurred. This issue is generally confined to the construction stage of the supply chain, though there is always the potential for fires to occur further upstream in transportation and manufacturing stages, for example. Site Manager 1 pointed out that ‘It is imperative relevant checks and inspection procedures are in place during construction to prevent the chance of a fire occurring.’

Overall feedback from the interviews conducted with Europeans highlighted that issues along the supply chain were generally unique to particular projects for unforeseen reasons such as lack of communication, weather, fire on projects and so on. The capacity of companies manufacturing and fabricating prefabricated timber elements wasn’t highlighted as a key issue as a large number of companies are vertically integrated and have enough production capacity to supply systems to projects at a relatively competitive time, cost and quality. Germany, Austria, Switzerland and to a lesser extent Scandinavian countries have significant manufacturing capacity for prefabricated timber elements. This was a key contrast to Australia and NZ where there is very little capacity in companies along the supply chain to produce elements for the market at a competitive cost, time and quality.

6.2.3 Cross Case analysis of Round 1 data

As outlined above, Round 1 interviews were undertaken with industry practitioners in Australia, NZ and four countries in Europe. These interviews established a number of key issues along the supply chain for prefabricated timber systems. This section presents a cross case analysis between Australia, NZ and Europe looking into what issues are common to all regions and what issues occur in one region and not another and, if so, why? The key issues and the regions in which they occur are listed in Table 6-5.

Table 6-5 Key issues affecting time, cost and quality of prefabricated timber systems

Key Issues	**Australia and NZ**	**Europe**
Fabrication capacity/process	✓	✗
Logistics/ transportation	✓	✓
Building code requirements	✓	✓
Design and detailing	✓	✗
Installation capacity	✓	✗
Fragmentation along the supply chain	✓	✗
Fires on construction sites	✗	✓
Communication along the supply chain	✓	✓

Table 6-5 highlights a number of issues that are common to Australia, NZ and Europe – these include logistics and transportation, building codes and communication along the supply chain. The logistics and transportation issue is one of those things that can occur in any region and ties into communication between manufacturers and site team to ensure systems arrive to site on time and as required for installation. Timber inherently expands and contracts when wet and exposed to the weather for long periods, so it's important that systems are adequately covered and protected during transportation. As highlighted in interviews, transportation issues can arise in any region and it is not a structural issue in the supply chain specific to any one region. One thing unique to Australia and NZ is that transportation costs are high due to a duopoly in shipping services in the region. This lack of competition leads to relatively high shipping costs when compared to global shipping rates. In Europe there is more competition in shipping services, so freight costs are generally cheaper.

Being an ETO product, prefabricated timber systems have to undergo design and detailing prior to production. Building codes in Australia, NZ and throughout Europe restrict the height to which buildings can be built in timber – primarily due to timber's inherently combustible nature. Generally timber buildings 4 storeys and higher are limited under prescriptive provisions. In many countries, performance-based designs are becoming an avenue to facilitate the acceptance of prefabricated timber systems in multi-storey buildings. These performance-based designs typically take longer to produce – this results in higher consultant fees and a longer and more onerous design and approval process.

In Australia, strategies such as CodeMark certification and changing the BCA are potential options to help achieve a more efficient building code approval process. In Australia and NZ, building codes are very similar, though throughout Europe each country typically has different code requirements and restrictions for prefabricated timbers use in multi-storey buildings. Overall building code approval for prefabricated timber systems in large multi-storey buildings presents as an issue in all regions analysed. Construction fires were highlighted as an issue unique to Europe, in particular the UK. This is most likely due to the fact that significantly more large timber buildings have been constructed in this region compared to Australia and NZ, so there's a greater chance of fires occurring.

Communication along the supply chain (up and down stream) was another issue highlighted as affecting time and costs in all regions. In Europe these communication issues were restricted more to the architect and the timber contractor during the design development stage, where there were sometimes issues with design details not being finalised and delaying manufacturing. Issues also occur between the head contractor and the timber contractor during the construction stage to ensure products arrive on site as per the installation schedule on the construction program. Similar communication issues also occurred in Australia and NZ as well as a number of others along the supply chain. These communication issues related to fragmentation are present in the Australian and NZ prefabricated timber supply chain because companies aren't integrated across all stages like they are in Europe. This concept will be discussed in greater detail throughout the rest of this chapter.

A number of issues including fabrication capacity/process, design and detailing, installation capacity and fragmentation along the supply chain were prevalent in Australia and NZ though weren't highlighted in Europe. These issues stem from larger structural issues in the supply chain in Australia and NZ, where there are fewer companies with the capacity to deliver prefabricated timber systems to the non-residential market at a competitive rate. Many of the companies, manufacturers in particular, are set up to service the residential housing market. This lack of capacity in the non-residential market is linked to the lack of demand for prefabricated timber systems. As there is demand for these systems in Europe a number of companies are set up to deliver prefabricated timber systems, and tend to have a high level of vertical integration either through ownership or alliances.

From these results it can be established that a number of the issues in Australia and NZ are directly related to the ETO companies responsible for the production of prefabricated timber systems. These findings lead into Round 2 interviews, where the business models and services offered by companies along the supply chain of prefabricated timber systems were looked into in detail. Then, following findings from Round 2 interviews, a cross case analysis is performed, highlighting in particular the differences between the prefabricated timber companies in Australia, NZ and Europe.

6.3 Round 2 Case Study

Following on from these findings in Round 1 interviews, a second round of interviews was undertaken specifically with the ETO companies involved in the production and delivery of prefabricated timber systems in Australia and NZ and also in Europe. These interviews were undertaken to obtain a greater understanding of how these companies are structured, their business models, the services they offered and why they were set up like this (i.e. whether market governed, and so on.).

The focus is on the services offered for non-residential construction, and in particular if and how they differ from the services offered in the residential market. Interviews were undertaken with senior leaders from ETO timber companies both in Australia and NZ and also in Europe. This section will reference each company by a number e.g. Company 1, Company 2, Company 3 and details of interviewees from each company will be referred to by their title. This section presents the findings from the interviews; and a detailed analysis of these interviews is undertaken later in this chapter.

6.3.1 Australia/NZ

Interviews were undertaken with 7 senior leaders from 7 companies in Australia and NZ which produce components for and completed prefabricated timber systems – details of interviewees in

Table 6-6.

Table 6-6 Round 2 Interviewee details – Australia/NZ

Interviewee	**Company - Reference**	**Company Type**	**Country**	**Work Experience**
Business Development Manager 3	Company 1	Manufacturer/ fabricator	Australia	15 - 20 years
Director 3	Company 2	Fabricator	Australia	20 + years
Director 4	Company 3	Fabricator	Australia	20 + years
Market Development Manager 1	Company 4	Manufacturer	NZ	15 - 20 years
Market Manager 1	Company 5	Manufacturer	NZ	15 - 20 years
Marketing Director 1	Company 6	Manufacturer/ fabricator	NZ	20 + years
Project Manager 4	Company 7	Manufacturer/ fabricator	NZ	20 + years

All of the timber companies interviewed currently offer products both in the residential and non-residential markets. The focus of the interviews was on the services offered by the companies for prefabricated timber products in non-residential construction. As highlighted earlier in this chapter, prefabricated timber products used in the residential market are typically MTS products in that they are essentially commodity products with very little value adding performed after the manufacturing stage. Conversely in the non-residential market, needs and expectations are more onerous – longer spans/sizes are generally required and each system is designed unique to each project. As a result they change from MTS to ETO products.

In Australia and NZ the largest companies involved in timber construction are focused on commodity production for the residential construction market. Interviews highlighted that this has occurred as traditionally there were no timber structural solutions available to compete with steel and concrete in non-residential construction – so they were unable to penetrate that market. Recently with the advent of new innovative prefabricated structural timber systems including EXPAN and CLT into Australian and NZ markets, timber companies now have the opportunity to compete with traditional forms of construction in non-residential construction, in particular multi-storey construction 3 storeys and above.

Table 6-7 below outlines the services offered by a number of major companies in Australia and NZ, producing prefabricated timber systems for the non-residential market. The key prefabricated timber systems being introduced into the Australian and NZ markets for non-residential construction are EXPAN and CLT. In Australia there is currently no CLT manufacturer and only a handful of companies that are capable of delivering EXPAN solutions. The supply chain for the production of these materials is broken up into two stages – manufacturing and fabrication. These processes are currently performed by different companies with no company integrated across both stages. This section will outline the structure and services offered by these companies in Australia and NZ. The following section will outline the current state of the art of timber companies producing prefabricated systems for the non-residential market in Europe. At the end of this chapter, a detailed cross case analysis between the companies along the supply chain in the two regions (Australia & NZ and Europe) will be conducted.

Table 6-7 Services offered/business models of timber companies in Australia & NZ

Reference	Company Type	Location	Typical services offered Non-residential projects				
			Structural engineering design	Detailing / shop drawings	Automated machinery - design integrates with machinery (CNC)	Logistics - to construction site	Install
Company 1	Manufacturer	AUS	✗	✗	✔	✗	✗
Company 2	Fabricator	AUS	✔	✔	✔	✔	✗
Company 3	Fabricator	AUS	✔	✔	✗	✔	✗
Company 4	Manufacturer /fabricator	AUS	✗	✔	✗	✔	✗
Company 5	Manufacturer	NZ	✗	✗	✔	✗	✗
Company 6	Manufacturer /fabricator	NZ	✗	✔	✗	✔	✗
Company 7	Manufacturer /fabricator	NZ	✗	✗	✗	✔	✗

AUS = Australia

Manufacturing

Company 1 and Company 5 are larger manufacturers of LVL. The LVL is produced in 1200mm billets and is predominantly used for residential detached housing – where it is ripped into standard widths and then sent to distributors and then onto timber merchants (see Figure 6.1). There is very little value adding to this product and it is very much a demand push strategy, where there is little interaction with the end customer. There is standard product information and some computer aided design software to assist engineers, though there is generally limited technical support – particularly for non-residential buildings.

LVL is the main input used in the development of EXPAN systems. EXPAN systems use LVL components and then fabricate them into building systems. This is done through a cutting, gluing and screwing process - Company 1 and Company 5 don't have much involvement with the product once it leaves their manufacturing facility. Market Manager 1 from Company 5 described the attitude on non-residential projects: 'the fabricator is supposed to tender on projects and as a manufacturer we don't want to be seen … we've got to respect the supply chain … we don't want to be seen dealing direct with the end user or the builder. We want to be selling to a reseller i.e. a distributor or a secondary manufacturer i.e. fabricator.' The question was asked to the manufacturers if they ever considered working with the end customer? Market Manager 1 from Company 5 replied: 'Maybe, though you would probably set up a separate business line/unit to do this … you would have to run it as a separate business … this is an issue from the manufacturer's point of view, as soon as you start doing that all the other secondary manufacturers such as fabricators, think you are kind of stealing work from them. So you can potentially lose them as customers and distributors in your other markets.'

Company 3, Company 4, Company 6 and Company 7 are manufacturers of glulam though they also have the ability to undertake fabrication work. Their core business function is to manufacture glulam – it just so happens that fabrication work of LVL and in turn EXPAN systems can be done using the same capital equipment (i.e. presses, gantry cranes, and so on) used to manufacture glulam. Market Manager 1 from Company 5 commented: 'Company 6 is a glulam manufacturer at the end of the day and even though they say they want to be involved in fabrication of LVL etc they really just want to make glulam … although we are trying to promote them – they're just not set up to do this fabrication and they might even see it competing with their core business, which is manufacture of glulam.'

The fabrication work is undertaken in the same workshop as the manufacturing work. When manufacturing glulam for residential projects these companies can sell products on to a distributor who then sells on to a timber merchant or builder – this is an expensive supply chain as more costs are added to the project by going through the distributor with little to no value added. Alternatively, manufacturers can deal directly with the builder, who deals with the end customer (client). This is more cost efficient as essentially one stage in the supply chain (distributor) is excluded from the process. At the end of the day Company 4, Company 5 and Company 6 are typically material suppliers only and don't tend to offer additional services such as design, shop drawings or installation.

Fabrication

Company 2 is a specialist timber fabrication company. There are a very limited number of these in Australia and NZ. Director 3 of Company 2 explained: 'there is a limited amount of capable fabricators and manufacturers, some fabricators have a preferred relationship with upstream suppliers … though as there isn't much competition in the industry there isn't many options to source material from.' Consultant 2 observed that 'Company 2 even though experienced, is difficult to work with at times … they also have limited capacity to undertake business development work and chase after projects … so even though they have the experience and skills they are limited in what they can do.'

6.3.2 Europe

Interviews were undertaken with 6 senior leaders from 6 manufacturing and fabrication companies in Europe which produce prefabricated timber systems. Similar to previous Round 2 interviews in section 6.3.1 Australia/NZ this section will reference each Company by a number e.g. Company 8, Company 9, Company 10, and interviewees are referred to by their titles. Details of interviewees and companies are outlined in Table 6-8.

Table 6-8 Round 2 Interviewee details – Australia/NZ

Interviewee	Company - reference	Company Type	Country	Work Experience
Business Development Manager 4	Company 8	Manufacturer	Austria & UK	15 - 20 years
Director 5	Company 9	Subcontractor	UK	20 + years
General Manager 2	Company 10	Manufacturer	Austria	20 + years
Market Manager 2	Company 11	Manufacturer	Switzerland	15 - 20 years
National Sales Manager 1	Company 12	Manufacturer	Austria & UK	20 + years
Project Manager 5	Company 13	Manufacturer	Italy	5 - 10 years

A summary of the services offered by a number of timber companies throughout Europe is shown below in Table 6-9. These companies typically have a number of different divisions or business units for the different products they manufacture. When developing prefabricated systems such as CLT and glulam for the non-residential and multi-storey residential markets (3 storeys plus) they typically have a separate business unit that deals directly with the end customer. The main prefabricated timber products that are produced for the non-residential markets in Europe are CLT and glulam. When providing these products to builders and end users in these markets, the companies typically offer a complete solution or service offering i.e. manufacture/fabrication, design and detailing & installation (see Table 6-9).

Table 6-9 Services offered/business models of timber companies in Europe

Company Reference	Company Type	Location	Typical services offered Non-residential projects				
			Structural engineering design	Detailing/ shop drawings	Automated machinery - design integrates with machinery (CNC)	Logistics - to project site	Install
Company 8	Manufacturer	Austria & UK	✔	✔	✔	✔	✔
Company 9	Subcontractor	UK	✔	✔	n/a	✔	✔
Company 10	Manufacturer	Austria	✔	✔	✔	✔	✔
Company 11	Manufacturer	Austria	✔	✔	✔	✔	✗
Company 12	Manufacturer	Austria & UK	✔	✔	✔	✔	✗
Company 13	Manufacturer	Italy	✔	✔	✔	✔	?✔

Company 8 is a large manufacturer of CLT in Austria, which also has a separate subsidiary in the UK. Business Development Manager 4 outlined they are a 'specialist solid timber supplier providing a "one stop shop" service – consultation, design, manufacture, supply and erection.' This 'one stop shop' service is a recurring theme across the companies shown in Table 6-9. Offering this 'one stop shop' model leads to a more integrated supply chain, which helps drive cost, time and quality benefits. Business Development Manager 4 also stated that 'we are involved from design concept to on-site completion … we undertake a collaborative working approach, developing sustainable and cost effective structural solutions by working with the project team from the earliest stages of the design process.' This model and service offering seems to be in stark contrast to the model provided by companies in Australia and NZ – this comparison will be touched on in greater detail in later in this chapter.

Company 8 is also flexible in their approach to the supply chain and the up and downstream services they offer. Sometimes they will offer only 'supply' and other times 'supply and erection' – they have the flexibility to change their services to meet the needs of builder and client. Design can also either be performed in-house or through working collaboratively with a novated engineer. In the situation of a novated engineer they may assist with detailing and converting engineered drawings to shop drawings used for manufacturing. This flexible approach is important due to the number of different project procurement methods used in construction. Company 8 will also outsource or subcontract a number of activities whilst still project managing and maintaining responsibility for these tasks. Transportation and installation contracts are at times outsourced to alternative subcontractors - whilst still managing these tasks under their scope of works or service offering. Company 11 and Company 12 are also large manufacturers that offer design and detailing expertise when required. They don't offer installation services though and National Sales Manager 1 from Company 12 argued that 'these services weren't necessary as there were enough experienced subcontractors able to do the work … also being directly involved on-site involved a number of inherent risks and associated liabilities.'

Company 10 has a similar business model to Company 8. General Manager 2 outlined that they 'offer a one-stop solution and provide consulting, engineering design, factory production and assembly, logistics and assembly on-site … one of the biggest advantages we think this model offers is that it provides one single point of contact to end users.' Having this single point of contact essentially mitigates fragmentation and helps streamline the supply chain. This helps drive cost, time and quality efficiencies. Company 13 like company 10 is a large manufacturer that also offers a 'one stop solution' to builders/clients, which involves a complete turnkey service offering for the prefabricated timber system.

Project Manager 5 from Company 13 supported the notion that through providing a complete service offering covering all stages of the supply chain time and cost efficiencies can be achieved. One interesting point raised by Project

Manager 5 and not touched on by any other interviewees was that 'by engaging with a client and offering them a complete solution by one company there is potential for a lack of quality in design and finished building solution … not in respect to aesthetic quality more so in regard to finished overall product … as it is in the interests of the company to provide them a solution only using our products, this may not be the best or innovative solution though as long as it maximises the use of the products we manufacture then the company sees it as a successful solution.'

Company 9 has a unique model compared to the other companies throughout Europe. It is based in the UK and doesn't perform manufacturing. It operates downstream from the manufacturing stage providing consultation, engineering, detailing and installation services. It provides the direct point of contact to the builder, and sources materials from a number of manufacturers. Director 5 from Company 9 remarked that 'they have a number of preferred suppliers and relationships with upstream suppliers though no official partnerships or alliances are in place… except the occasional project partnership.'

There are arguments for and against having a direct affiliation with one supplier though Director 5 explained that 'it allows us to source materials from a number of different suppliers… this helps us achieve competitive rates.' Structural Engineer 3 also works for Company 9 and outlined that the company didn't offer installation services when it first started – mainly focusing on design and detailing services. He mentioned that 'During projects in the early days of the company's operations contractors didn't have experience installing the prefabricated timber elements … this meant a number of mistakes were made and the possible time savings of using lightweight timber elements weren't being achieved … so we changed our business and began to offer installation services as well.' As a result of this offering, time, cost and quality issues during the construction stage as well as logistics from manufacturing to sites have been improved. Director 5 supported the results from Round 1 interviews in Europe describing the biggest potential issues to cost and time along in the supply chain as 'realistically more towards transportation logistics … ensuring lead times and deliveries are coordinating in a manner that they can arrive just-in-time to site … though it's just a matter of organizing logistics accordingly.' Being responsible for the procurement of materials from manufacturer right up to final in-place installation helps address these issues.

6.3.3 Cross Case Analysis of Round 2 data

Following on from Round 1 analysis it was established that the key issues along the supply chain that affect the performance (time, cost and quality) of prefabricated timber systems in Australia and NZ were directly related to the companies involved in the production and delivery of these systems. As a result Round 2 interviews were undertaken with a focus on the ETO companies in the prefabricated timber supply chain to gain a greater understanding of their business models, services offered, markets they operate in and how these relate to issues highlighted in Round 1. Results of these interviews are outlined in Chapter 6 and this following section provides a cross case analysis between Australia, NZ and Europe.

The prefabricated timber market in Europe has been around for a significantly longer time than Australia and NZ. In Europe glulam has been manufactured and fabricated into large structural components for over 50 years, and CLT for the last decade or so. Compare this to Australia where there is no CLT manufacturer and only a small number of LVL manufacturers that have been in operation for 10 - 20 years. Glulam, which even though it reached Australia in the early 1950's has been a relatively niche industry, focused on small scale architectural projects such as public assembly buildings and bridges (FWPA 2007). In Europe a large number of companies offer a fully integrated solution to customers. This allows a company to value add over the supply chain, which not only provides access to higher revenue, but also provides a higher level of success in projects and in turn satisfaction to clients.

The Australian and NZ the prefabricated timber supply chain is fragmented. No company offers a fully integrated model like those seen in Europe (refer to Table

6-9). This is likely related to the fact there hasn't been the demand for large non-residential multi-storey timber buildings, primarily due to the lack of available prefabricated timber systems capable of meeting the performance requirements of the non-residential sector. With the advent of the EXPAN system and the high interest in CLT, a demand and in turn market for such systems is starting to develop – this is demonstrated by Lend Lease, one of Australia's largest property developers, recently constructing in Melbourne, Australia the tallest multi-residential apartment block in the world out of CLT (Lease 2011). At present there is a chicken and egg situation, where developers, contractors and designers alike have shown interest in prefabricated timber systems though they have expressed concerns with high costs, long lead times, lack of design and installation skills, and so on, as outlined in the interview findings and supported in the literature (Bayne & Taylor 2006; Nolan 2010).

In Europe timber companies supplying the non-residential market have integrated models encompassing design and detailing, manufacturing/fabrication and installation. Similar models are also common in steel companies competing in the non-residential market in Australia. As outlined in Round 2 interviews, timber companies in Australia and NZ have been focused on the residential market and don't yet offer these services. It is also important to highlight in Australia and NZ that the commercial construction environment is substantially different to the residential market. If companies are going to be successful in producing these new innovative systems time and cost competitively they need to structure their businesses to suit. As highlighted in chapter 4, structural contingency theory outlines there should be a fit between the organizational processes and the environment (Burns & Stalker 1961; Lawrence & Lorsch 1967). It outlines that company structures that match the environmental requirements should perform more successfully than those that don't and under-performing companies may decide to adopt a new business model that better fits the environment. When applying this theory to supply chains, the supply chain as a whole should be structured to suit the environment (Flynn, Huo & Zhao 2010). Research indicates that it requires significant capital investment and time to establish structural changes in organizational configurations; as a result companies rarely undertake the process.

As outlined earlier prefabricated timber ETO companies in Europe have vertically integrated models in order to meet the needs and requirements of the non-residential and multi-storey markets. Large capital costs are typically required for vertical integration and this strategy is typically most suited to stable and mature environments (Harrigan 1984). In Australia and NZ the market for prefabricated timber systems is still in its infancy: 'the idea of vertical integration is anathema to an increasing number of companies. Most of yesterday's highly integrated giants are working overtime at splitting into more manageable, energetic units – i.e. de-integrating. Then they are turning around and re-integrating – not by acquisitions but via alliances with all sorts of partners of all shapes and sizes' (Grant 2007). Using these ideas as a base there is the possibility of adopting strategic procurement strategies between a number of firms in the ETO supply chain to offer an integrated 'solutions approach' for prefabricated timber systems in which the supply chain is an extension of the organisation.

6.4 Conclusion

This chapter presented key points from the findings from a total of 55 interviews undertaken with industry professionals involved in various stages of the supply chain of prefabricated timber systems. Interviews were undertaken in 2 Rounds. A total of 42 interviews were performed in Round 1. They were undertaken in both Australia and NZ as well as throughout Europe. Round 1 interviews established the overall issues along the supply chain that affected time, cost and quality in the different regions. The key finding from Round 1 was that in Australia and NZ there is a lack of capacity in the fabrication stage of the supply chain, and the supply chain overall is fragmented with a large lack of integration between different companies along it. Moreover, companies are more focused on the residential market – though this is primarily demand driven. In Europe there is a more mature market and as a result more capacity in the production stage.

Round 2 interviews were then performed specifically with the companies involved in the manufacturing and fabrication of prefabricated timber materials – once again both in Australia, NZ and Europe. Key findings from Round 2 interviews were that in Europe companies generally offer a 'one stop shop' including consultation, design and detailing, manufacturing/fabrication, logistics and installation. This integrated model helps produce cost and time competitive systems at a high level of quality. In contrast, in Australia and NZ, aside from limited capacity, there is also very little integration or communication between supply chain participants (i.e. manufacturing, fabrication, design and installation).

Following interview results an analysis of these findings was conducted for Round 1 and Round 2. In both of these rounds a cross case analysis was performed between results in Australia, NZ and Europe. Through using these interview findings, conducting further industry analysis and taking a strategic procurement perspective – structural contingency theory will be used to help provide a top-down analysis and develop a preliminary supply chain model incorporating the companies along the supply chain for prefabricated timber systems. It is intended this model will help drive cost, time and quality issues in the Australian and NZ markets. This model will be developed in the next chapter (Chapter 7 – Model development) and will be devised from a combination of theory and primary data obtained from interviews.

Using structural contingency theory as a basis a hypothesis is established that in order for the supply chain for prefabricated timber products in Australia and NZ to improve its performance – the entire supply chain incorporating all the companies involved will need to change its structure to suit the environment they operate in. The companies are currently focused primarily on the residential market, in particular detached housing. If these companies want to be successful in the non-residential market and move away from their reliance on the residential market, they will need to change their business structures to suit the new environment. Chapter 8 will then empirically test this hypothesis with three building case studies of recent non-residential projects utilising prefabricated timber structural systems.

Chapter 7 Model Development

7.1 Introduction

In this chapter a supply chain model for prefabricated timber systems is developed using a combination of interview data from chapter 6 and strategic procurement SCM literature. A deductive research method using structural contingency theory is adopted to help develop the supply chain model. In order to address time, cost and quality issues, individual dimensions of supply chain should be aligned to suit the environment of the market the companies operate in to achieve the best performance. Companies in Australia and NZ need to change their business models and how they interact with the wider supply chain. upstream and downstream. To improve the performance of prefabricated timber systems, companies should change their structures and the supply chain to suit the new environment – moving from the residential to the non-residential market.

This chapter firstly reviews the application of structural contingency theory to the supply chain of prefabricated timber systems in Australia and NZ. The market needs and expectations of the non-residential construction market are outlined and then a detailed analysis of the Australian and NZ prefabricated timber system industry is undertaken through the use of Porter's five forces analysis (Porter 2008). This five forces analysis is undertaken from the perspective of a fabrication company. This analysis follows on from the data analysis section in chapter 6. The differences between residential and non-residential markets will then be outlined, with a particular focus on the market needs and expectations of structural systems in the non-residential markets. This will then lead into how structural contingency theory can be applied to prefabricated timber systems and the companies that produce these systems. Finally, through the use of a framework, a supply chain model will be developed for prefabricated timber systems used in non-residential markets in Australia and NZ. The model is termed specialist business entity (SBE) and will have a number of designers, fabricators and installers under its umbrella. These businesses would form a network through strategic alliances and partnerships. This would accumulate the necessary resources to undertake a number of projects at the same time. This capacity would still be relatively limited in the short term though it is envisaged that it would grow. Strong project management skills from the lead entity would be required.

Following this chapter, three building case studies in Chapter 8 will empirically test the model and structural contingency theory in relation to prefabricated timber elements. The hypothesis remains as previously stated – unless ETO companies involved in the production and delivery of prefabricated timber systems in Australia and NZ change their structures to suit the non-residential environment and better meet the needs and expectations of customers in this market, their performance will be low and a predictable range of problems will recur.

7.2 Structural contingency theory and prefabricated timber systems

Following on from Chapter 2, structural contingency theory refers to the consistency between an organisation's structure and the strategy it pursues in its external environment. In the context of the supply chain, when its external environment changes up or downstream, i.e. customers and suppliers, a company should respond by establishing and then implementing strategies to maintain fit in both internal structural characteristics and external environments (Hambrick 1983; Kotha & Nair 1995; Tushmanm & Nadler 1978).

As aforementioned this research aims to test structural contingency theory when applied to the supply chain and ETO organisations involved in the production of prefabricated timber systems in Australia and NZ, from the hypothesis that unless companies involved in the production and delivery of prefabricated timber systems in Australia and NZ change their structures to suit the non-residential environment and better meet the needs and expectations of customers in this market, the companies' performance will be low and a predictable range of problems will recur.

The concept of 'fit' is of critical importance to organisations involved in the production and delivery of prefabricated timber systems in Australia and NZ. In those countries manufacturers of EWP e.g. LVL are currently commodity producers who serve the local residential construction markets and other Pacific Ocean countries such as Japan. Commodity production typically requires national or international commodity markets, while construction markets are generally local or regional. Multi-storey non-residential construction due to increased regulatory and design requirements are far more service intensive than residential housing. EWP manufacturers, making the key input to prefabricated timber systems, have focused on commodity production and this has resulted in withdrawal or lack of involvement with the building market, except for providing general product information (Nolan 2010).

Nolan (2010) undertook a survey that revealed EWP manufacturers in Australia and NZ typically don't know where or for what buildings their products are used. This organisational structure 'fits' the environment of the residential housing market – though this lack of engagement with the supply chain doesn't fit with the environment in non-residential commercial construction markets. A few specialist structural fabricators offer integrated services, though their capacity is very limited. Table 7-1 below outlines characteristics of ETO organisations involved in the production and delivery of prefabricated timber systems.

Table 7-1 Manufacturers and fabricators of prefabricated timber systems in Australia and NZ

Manufacturers & fabricators organizational characteristics	**'Fits' with Residential housing environment**	**'Fits' with Non-residential construction environment**
Production capacity geared towards small projects	✓	✗
Simple administrative requirements	✓	✗
Use of simple contracts	✓	✗
Typically don't provide install services (left to builders)	✓	✗
Typically offer relatively limited design services	✓	✗
Have direct communications with customers & change services according their needs	✗	✗

As detailed in Table 7-1 the non-residential construction market in contrast to the residential market involves much larger projects in terms of size and complexity. Non-residential projects typically have more complicated administrative requirements, complex contracts than their residential counterparts. Typically large tier one commercial builders require 'supply and erect' services which can exclude fabricators from tendering for projects unless they offer installation services. Non-residential projects also have structured progress payment systems that may not fit the current organizational structure or suit cash flow requirements of small fabricators. Major Australian volume home builders are more often also now looking to engage subcontractors on a supply and install basis. This is good way for these builders to mitigate risk and place all of the responsibility onto the contractor. It is still common practice, in residential housing construction, builders erect their own structural frames; fabricators generally do not offer erection services. Non-residential construction involves higher design and regulatory requirements. There is also a higher level of complexity in prefabricated systems relating to spans, connections, mechanical and electrical services and façade integration. These needs and expectations of the non-residential construction market are outlined in more detail in section 7.3 below.

7.3 Non-residential market needs and expectations

There are a number of market needs and expectations for new innovative products wishing to enter the construction market. These needs and expectations are generally benchmarked against existing products and current industry norms. The construction market is notoriously competitive and if a new product wishes to take market share from existing products it would need to adhere to numerous markets needs and expectations (Nolan 2010). To be successful it would need to offer benefits/advantages over existing products that customers value and deem important (i.e. costs, time and quality) for them to adopt the new product. Prefabricated timber systems have some advantages over traditional systems. They are inherently lighter than traditional steel and concrete structural systems, which can lead to potential cost savings from fewer foundation materials and faster installation on-site. LCA studies (John et al. 2011; John et al. 2009; Page 2006; Perez 2008) have shown they are more environmentally friendly than traditional forms of construction; Table 4-5 in chapter 4 compares details on the findings of these LCA studies. In order to be commercially viable a number of market needs and expectations must to be addressed. These will help provide further background information to the development of a supply chain model and are outlined below;

- Cost – accurate cost data & certainty

Cost is a critical factor clients, designers and contractors consider when selecting a particular structural system for a building. It is important for new systems to be comparable or cheaper in cost. It is also important to have accurate cost data available and to demonstrate that the system can be delivered to the cost that was originally estimated. There is a large amount of accurate cost data on steel and concrete systems. In Australasia limited new prefabricated timber systems are being used in non-residential buildings – as a result there is limited data on the final as-built costs of the systems. The issue here is that when a QS prices a project for a client, there is potential to add contingencies (or underestimate) the price of these new systems to allow for uncertainty risks.

- Lead times – supply & erection capacity

The structural works trade is typically on the critical path of non-residential construction projects. If items in this package are delayed it will inevitably delay the completion date for the entire project. It is imperative that new prefabricated timber systems can be supplied to site on time and installed efficiently.

- Quality – assurance that product arrives to site as per specifications and not damaged from transportation

Quality is another key component on construction projects. It is important that measures are in place to ensure prefabricated systems arrive on-site in a condition detailed in the specifications. This is particularly important for timber systems as they are susceptible to damage from water and wind, for example, during transportation or from being left out on-site.

- Single point of responsibility

In residential projects structural materials are usually supplied to site and then installed by the builder where in non-residential projects head contractors typically require 'supply and erect' services for structural systems. This need was recently demonstrated on a new institutional building in Melbourne, Australia where prefabricated timber systems were specified and when the contractor went out to tender no-one in Australia and NZ could offer a 'supply and install' package. This is important for head contractors as it allows them to have a single point of responsibility for this process. In particular, with the structural package being on the critical path it is important that there are minimal issues with it.

- Occupational Health & Safety – system can be installed safely

The construction industry is renowned in general for its poor safety record. Prefabricated timber systems have the potential to be safer to install though it is important that contractors and or specialist installers are aware of how to install these systems safely (FWPA 2007).

- Building code approval (fire, acoustics, structural etc.) – meets Building Code of Australia BCA requirements either Deemed-to-satisfy (DTS) or Alternate Solutions.

All buildings in Australia have to meet the requirements outlined in the BCA. New innovative systems may not adhere to DTS provisions and may require a performance based Alternate Solution. It is important that the technical data/testing is available or it may result in comprehensive testing having to occur whilst the construction contract is running. These building code issues, in particular fire, acoustic and structural concerns, are covered in detail in literature review Chapter 4.

- Design capability – industry expertise to confidently design structural systems, including façade connection to frame, services integration & standard connection details

In order for a new system to be successful it is imperative that there are resources available to aid designers. If it is difficult to design, designers are going to be less willing to specify and support a new system. Design guidelines, industry seminars and hotlines that offer advice are useful ways to help address this.

- Standard performance requirements i.e. grid layouts, floor-to-floor heights and overall building height

In commercial office applications in Australia there are certain expectations or industry norms for grid layouts and floor-to-ceiling heights. In A grade commercial office buildings floor-to-ceiling heights have to be 2700mm and typically floor-to-floor heights are around 3800mm (the smaller the better). So that leaves 1100mm for structure, services, finishes, ceiling etc. For longer spans this may present an issue for new timber systems.

- Sustainability qualities – Corporate Social Responsibility (CSR), marketing, attract tenants etc.

Going forward as climate change continues to come to the forefront, it will become increasingly important for buildings to be sustainable in nature. As buildings become more operationally energy efficient, the embodied energy of materials will become a higher proportion of life cycle energy. Prefabricated timber systems are inherently more environmentally friendly than traditional forms of construction (John et al. 2011; John et al. 2009; Page 2006; Perez 2008).

- Client and tenancy demand – willing to pay a premium?

Client and tenancy needs are one of the most, if not the most critical needs to address. Demand for clients will be driven by the aforementioned expectations i.e. cost, time, quality etc. and in order to be commercially viable new timber floor systems will have to create a value proposition to clients that meets and exceeds these requirements and also provides other benefits such as natural warmth and aesthetics.

'Understanding customers' needs and expectations and supply chain uncertainty (demand and supply) that a company faces is essential for developing the right capabilities or abilities to serve the markets' (O'Brien et al. 2009 p. 3). Haag, Baltzen and Phillips (2008 p. 109) outlined that a key principle of SCM is to 'Segment customers by service needs, regardless of the industry, and then tailor services to those particular segments.' This understanding of the markets needs and expectations will help provide background information for the supply chain model later in this chapter. The supply model will aim to address these market needs and expectations and the issues highlighted in data obtained from interviews in chapter 6. By doing this the supply chain model will help improve the supply chain for prefabricated timber systems. The following section will help obtain a greater understanding of the prefabricated timber system industry in Australia and NZ.

7.4 Porter's five forces analysis

The five competitive forces that shape strategy constitute a framework that is used to analyse industry competition and profitability. These five forces are shown in Figure 7.1 below:

- Bargaining power of suppliers

- Bargaining power of buyers
- Threat of new entrants
- Threat of substitute products or services
- Rivalry among existing competitors

The 'awareness of the five forces can help a company understand the structure of its industry and stake out a position that is more profitable and less vulnerable to attack' (Porter, 2008 p. 78). Even though this framework is predominantly used as a strategy tool, it has relevance to this thesis, as it can help explore the environment in which a company or product operates. This helps provide further background information on the industry in which prefabricated timber elements operate. It also helps understand the power relationships between buyers and suppliers, which are very important when developing a supply chain model (Cox 2009; Cox, Ireland & Townsend 2006).

Smith (2008) undertook a five forces analysis on post-tensioned timber systems and his analysis was undertaken from a product perspective. Porter's framework is geared toward companies and understanding what impacts their profitability in a particular industry. The focus company in the five forces analysis in this thesis will be a fabrication company – in particular a fabrication company in Australia and NZ, focusing on the development of EXPAN systems using LVL as a raw material input. The reason why a fabrication company is used in this analysis is that companies like this one play a critical role in the ETO supply chain of prefabricated timber systems and interviews highlighted this stage of the supply chain as one of the biggest issues. This analysis will help obtain more knowledge on this, which will be used in the supply chain model developed later in this chapter.

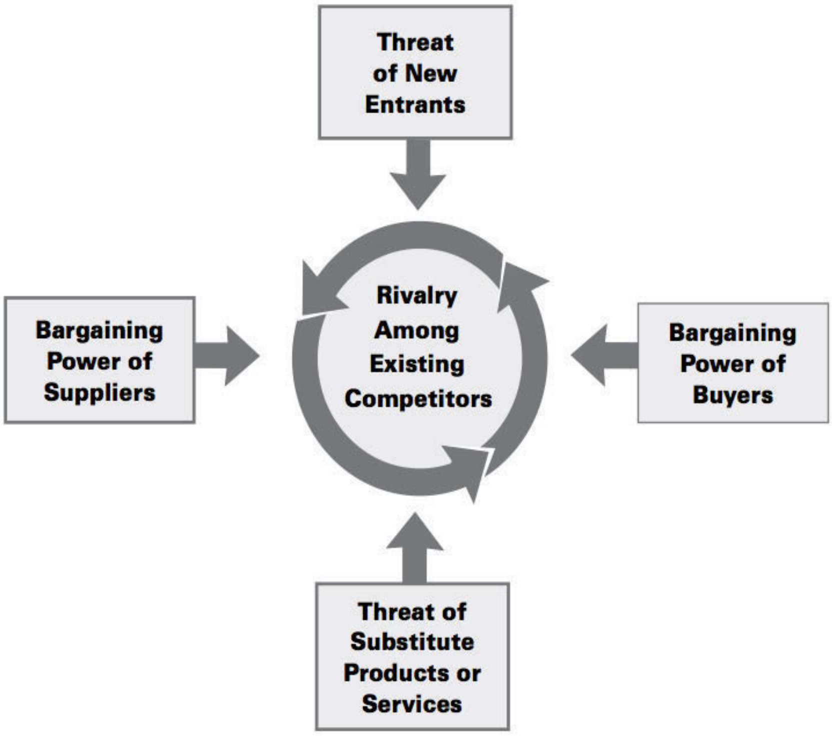

Figure 7.1 The Five Forces That Shape Industry Competition

Source: Porter (2008)

7.4.1 Bargaining power of suppliers

The key component input during the fabrication of EXPAN systems is LVL. Three main players dominate the manufacturing of LVL in Australia and NZ. Aside from the three main players there is one smaller manufacturer in NZ and another large distributor in Australia that distributes LVL from America and Europe. As a few large suppliers dominate this market, they have power over the fabrication companies, as there are limited substitutes for this product. There is an oligopoly market, and the risk that, if demand continues to increase, the LVL manufacturers could charge the fabricators higher rates, particularly if there is high demand for LVL from the residential market. There is also the risk that these manufacturers might integrate forward into the fabrication stage. Even though this increases competition for fabrication companies, it could be a good option for manufacturers as they would be able to achieve further margins downstream. Being significantly larger in size than current fabrication companies they have the potential to invest in larger capital equipment such as

Computer Numerical Cutting (CNC) machinery to make the fabrication process more cost and time efficient. This could lead to cheaper and more efficient production of prefabricated timber systems.

7.4.2 Bargaining power of buyers

Commercial customers are more sensitive to price than residential customers of prefabricated timber systems, particularly on commercial office projects where the owner is not the occupier and has tenants in the buildings. Developers and owners (typically investment funds or institutional investors) are primarily concerned with the CAP rate of the project. Head contractors and clients are the end customers for prefabricated timber systems. Steel and concrete are traditional structural solutions used in non-residential construction and have proved to be a viable cost effective option for these customers over the years. Head contractors typically operate on low margins and are price sensitive. On projects where they have tendered and won Design and Construct (D&C) contracts they are generally looking to put forward the most cost effective structural solution. It is relatively easy for them to switch from one structural system to another and not endure any excessive costs. The customers in this sense have bargaining power over fabricators of prefabricated timber systems.

7.4.3 Threat of new entrants

The barriers to entry for companies wanting to enter into the fabrication space are medium to high. The fabrication of prefabricated timber systems (i.e. EXPAN) requires relatively high initial investments and fixed costs. A large warehouse is needed and Computer Numerical Cutting (CNC) machinery is a beneficial investment to help produce systems cost and time effectively. Optimal fabrication techniques lie with those who have experience in this process. The security of important resources, in particular qualified expert staff. It takes experience and trial and error to establish what are the most cost and time efficient fabrication processes. For specialist fabricators there is also the threat of manufacturers vertically integrating downstream and smaller scale glulam companies undertaking the same task as them. Some glulam companies are also more willing to get into the fabrication space, though as it is not their core business some are reluctant to do so.

7.4.4 Threat of substitute products or services

The threat of substitutes for prefabricated timber systems is high. Steel and concrete have been the traditional forms of construction in non-residential construction in Australia and NZ. These alternative products, depending on the project, generally offer lower prices and better performance parameters for the same purpose. These products are currently common practice, so there are switching cost issues and designers (i.e. engineers and architects), who have a large amount of experience using concrete and steel, may have a loyalty to these products and be reluctant to adopt and try new innovative prefabricated timber systems. For fabrication companies focusing on the production of EXPAN and similar prefabricated timber systems the threat of substitutes is one of the greatest issues that will affect their profitability and ability to charge high rates for systems.

7.4.5 Competitive rivalry among existing competitors

Competitive rivalry is relatively low as there are relatively few specialist fabricators of EXPAN and similar systems in Australia and NZ. Only a handful of specialist fabricators operate in Australia and NZ and they are all of the same size, typically small companies with fewer than 10 people. Differentiation between these companies is related to quality and cost, with service and reputation major factors too. The barriers to exit are also relatively high for these companies as when they have invested capital in machinery and a workshop to produce these systems it isn't easy to simply move over into other products.

Porter's five forces framework is predominantly a strategy tool and this thesis is focused towards supply chain management. This five forces analysis albeit relatively brief has provided further understanding of the prefabricated timber system supply chain in Australia and NZ. In particular looking at the industry from a fabrication company perspective has helped provide detail on the power relationships between buyers and suppliers and the impact that substitute products (i.e. steel and concrete) have. There are a number of different ways organisations and the supply chain can be set up/structured to deliver ETO products. The following section will review a number of different ETO models. These models are not specifically for prefabricated timber systems, though they present a number of useful ideas that can be incorporated into the development of the supply chain model in this thesis.

7.5 Model development conceptual framework

As outlined in chapter 3, viewing the supply chain from a strategic perspective led to revolutionary changes, where supply chains began rethinking their organisational structure to suit their environment (Christopher 2011). This thinking stems from structural contingency theory – an organisational theory which states there should be a fit between the organizational processes and the environment in which the company operates. Structural contingency theory outlines that a company structure (business model) that matches the environmental requirements should perform more successfully than those that don't (Burns & Stalker 1961; Donaldson 2001; Lawrence & Lorsch 1967). When applying this theory to supply chains, the supply chain as a whole should be structured to suit the environment (Flynn, Huo & Zhao 2010). In order to meet ever-changing market demands, organisations have restructured to form a 'network', where the supply chain is an extension of the organisation (Christopher 1998b; London 2004).

A supply chain model for prefabricated timber systems will be developed using a combination of interview data, industry analysis and literature. A top-down approach using structural contingency theory is adopted to help develop the supply chain model. In order to address performance (time, cost and quality) issues, individual dimensions of the supply chain should be aligned to suit the environment and the market in which the companies operate. Following structural contingency theory, companies in Australia and NZ should change their business models and how they interact with the wider supply chain (upstream and downstream) in order for prefabricated timber systems to be successful in multi-storey non-residential construction. Companies will need to change their structures and the supply chain to suit the new environment – facilitating movement from residential to non-residential market.

Azambuja & O'Brien (2009) developed a conceptual framework (see Figure 7.2) to model construction supply chains. This framework will be used to support the development of a comprehensive supply chain model. The steps in this framework will be described in detail in the following section and then these steps will be used as a framework to develop the supply chain model in this thesis.

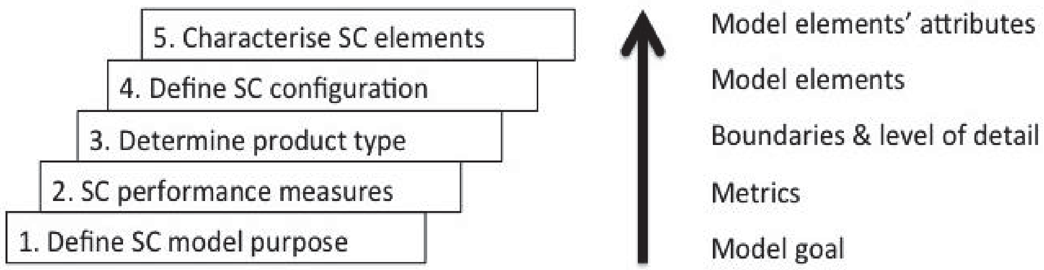

Figure 7.2 Conceptual framework
Source: (Azambuya & O'Brien 2009)

7.5.1 Framework steps in detail

The first step of the framework is to define the purpose or goal of the supply chain model. There are a number of possible purposes that have been modelled in manufacturing and construction supply chains over the past decade including:

- Evaluate the best configuration of organisations in supply chain
- Reduce product lead time (eliminating or combining activities)
- Evaluate buffering decisions
- Evaluate production decisions
- Evaluate transportation decisions
- Assess supply chain costs
- Illustrate the supply chain information coordination (IT application)

- Assess the impact of product complexity on the supply chain response time

Once the modeller has defined the purpose or goal of the modelling exercise the next step is to establish a set of performance measures. It is imperative that these measures are associated with the model goal. For example, if the goal of the model is to support lead-time reduction, metrics (performance measures) that will be fundamental to model development will include processing time, engineering (design) time and manufacturing/assembly time.

The third step in the process is to determine which type of product is going to be modelled. A model for an ETO product needs to include various processes executed by different actors, for example designers, engineering firms, general contractors and suppliers. Due to the increased complexities of ETO products, several information flows need to be taken into account when modelling these types of product. The outcome of this step is to establish the supply chain model boundaries and level of detail, i.e. which supply chain processes are going to be included in the model. Table 7-2 below outlines suggested model boundaries and processes based on different technologies.

Table 7-2 Different technologies – suggested model boundaries and processes

Product Type	**Manufacturing environment**	**Supply chain boundaries**	**Supply chain processes**
Made-to stock (MTS)	Assembly line or continuous flow	MTS supplier, warehouses, subcontractor or contractor, job site	Subcontractor or contractor places order, supplier checks product availability, picks and delivers, unloads on job site, product installation.
Assembled-to-order (AT0)	Assembly line	ATO supplier, upstream supplier or critical raw material (RM) component,	Subcontractor or contractor places order, supplier checks RM availability, either starts assembling the product if RM available or needs to wait for RM, temporary finished good (FG) inventory, delivery, unload on job site,

		subcontractor or contractor, job site	product installation.
Made-to-order (MTO)	Job shop or batch	MTO supplier, upstream suppliers or critical RM components, contractor designer, owner	Contractor receives detailed design and places order, supplier checks design and order, if information is complete and RM available it starts manufacturing, otherwise waits for RM or contractor, designers and owners review and approve changes, product manufacturing, temporary FG inventory or immediate delivery, unload on construction site, installation
Engineered-to-order (ETO)	Job shop	ETO supplier, upstream suppliers of critical RM components, architect, owners, engineers, contractor	Supplier either fully designs or only detail the design received from the engineering company, the owner checks the detailed design, if design is accepted the supplier can start manufacturing the product, otherwise it waits for owner response, product manufacturing, temporary FG inventory or immediate delivery, unload on construction site and installation

Source: Azambuya & O'Brien (2009)

The fourth step in the framework is the definition of the supply chain configuration. In this step the model elements including supply chain actors, processes, activities, material flow, information flow, inventory buffers and resources are arranged to build the supply chain model. The boundaries and processes included in step three help support the supply chain configuration. Then, in order to configure the supply chain, the various processes are assigned to various actors in the chain who execute them. The relationships between the actors and processes can then be established as along with the logical sequence of the process.

The fifth and final step of the modelling framework is to characterise the supply chain model elements. This step encompasses the description of each of the model elements in order to provide more detailed and complete information on the supply chain model. These descriptions help users to understand the model behaviour. Each model will have its own set of attributes, which are necessary for the creation of prescriptive models as well as improving the descriptive power of construction supply chain models.

7.5.2Review of current supply chain

Prior to development of a supply chain model for prefabricated timber systems and companies involved in its supply chain, it is important to revisit the current supply chain to highlight current issues. Following on from Chapter 6, a model of the current supply chain for prefabricated timber products in Australia and NZ will firstly be reviewed and critiqued. Interview findings identified a number of issues along the supply chain, including fabrication capacity, design and detailing, installation and fragmentation. These issues stem from larger structural issues, where there are limited companies with the capacity to deliver prefabricated timber systems to the non-residential market at a competitive rate. This lack of capacity can be linked to lack of demand in the non-residential market and the fact that companies, particularly manufacturers, are set up to service the residential housing market.

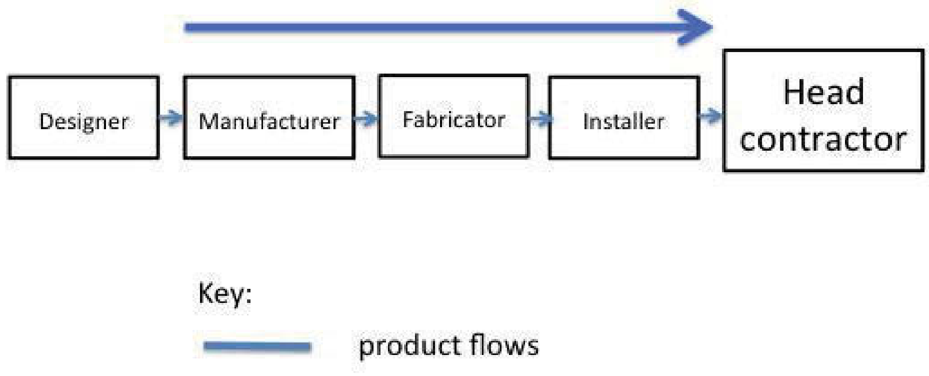

Figure 7.3 Current supply chain for EXPAN products in Australia/NZ

As depicted in Figure 7.3 the manufacturer has little communication with the fabricator and primarily supplies commodity products to the fabricator. The Porter's Five Forces analysis earlier in the chapter highlighted the important role these manufacturers play in the supply chain and the power they have as suppliers. There is also typically limited communication between designers and fabricators. The fabricator can purchase material directly from the manufacturer or from the distributor at a higher rate. Fabricators in Australia and NZ are generally smaller companies with less than 10 people and have direct communication with the head contractor. Head contractors typically want to deal with a larger entity for structural packages, and typically let the structural package out as supply and install. No company offers a fully integrated model like those seen in Europe (Refer to Table 6-7 in Chapter 6). At present there is a situation where developers, contractors and designers alike have shown interest in prefabricated timber systems but have expressed concerns with high costs, long lead times, lack of design and installation skills, etc. (Bayne & Taylor 2006).

In Europe timber companies supplying the non-residential market have integrated models encompassing design and detailing, manufacturing/fabrication and installation. Similar models are also common in steel companies competing in the non-residential market in Australia. The model developed in the following section will aim to address the issues highlighted in case study interviews in chapter 6. Lessons learned from Europe will help provide ideas for the model in an Australian and NZ context.

7.6 Model development

Using Azambuya & O'Briens' (2009) conceptual framework as a guide, a supply chain model is developed for prefabricated timber structural systems in Australia and NZ, with a particular focus on EXPAN systems. As detailed in Chapter 4 of the literature review and case study interview findings in Chapter 6, EXPAN systems are seen to present a viable option for timber to enter the non-residential construction market. This model is intended to address the issues raised in interviews in chapter 6 and better meet the needs and expectations of the commercial construction market. Following on from 7.5.1 Framework steps in detail above, the five steps outlined in Azambuya & O'Brien's (2009) conceptual framework will be followed to develop a supply chain model for prefabricated timber structural systems in Australia and NZ.

7.6.1 First step – define supply chain model purpose

The first step is to determine the goal or purpose of the model. Ensuring prefabricated systems can be delivered at a competitive cost and time and can meet the needs and expectations of customers is imperative to their successful commercialisation into the construction market. As a result the main goal for the supply chain model in this research is to develop an ideal supply chain configuration of organisations involved in the production of prefabricated timber structural systems in Australia and NZ including:

- Establish the supply chain configuration to address issues and fulfill market needs and expectations in the non-residential environment
- Show which company is responsible for each process (ownership decisions)
- Outline relationships between members in the supply chain

7.6.2 Second step – supply chain performance measures

Now the purpose/goals for the supply chain model have been established, the second step in the model development is establishing sets of performance measures (metrics) for each model goal, which are outlined in Table 7-3. The data (metrics) for this supply chain model are developed from a combination of data from semi-structured interviews (chapter 6), industry analysis (market needs and expectations and Porter's five forces analysis) and is also supported with strategic procurement literature and structural contingency theory.

Table 7-3 Supply chain performance measures (metrics) associated with model goals

Supply chain model goal	Metrics	Data source
Evaluate and develop the ideal supply chain configuration for prefabricated timber structural systems		
Establish the supply chain configuration to best fulfil demand → address issues and fulfil market needs and expectations in non-residential environment		Interviews, industry analysis, strategic procurement literature
Show which company is responsible for each process (ownership decisions)		Interviews
Outline relationships between members in the supply chain	Contracts used, partnerships/alliance agreements	Strategic procurement literature

7.6.3 Third step – determine product type

The third step in the process is to determine which type of product is going to be modelled. As detailed previously, prefabricated timber systems are ETO products. ETO products have the decoupling point at the design stage – where each product gets conceived at the design stage. Table 7-3 above outlines the suggested model boundaries and processes for different products. ETO products include various processes executed by different actors, for example designers, engineering firms, general contractors and suppliers. ETO supply chains inherently have more complexity than products like MTS, ATO and MTO. The supply chain boundaries for the model are going to follow the boundaries outlined in the introduction of the thesis. The focus of the model is on EXPAN prefabricated timber products where manufacturing and fabrication are separate stages. This model could be devised to incorporate CLT, though generally the manufacturing and fabrication processes are done at the same stage. There is potential that this model could be adopted for CLT in Australia and NZ, particularly where a manufacturer produced blank CLT panels and then obtained the fabrication or cutting of these panels by another entity.

In theory the model should be able to be adapted for EXPAN and CLT – though it is more geared towards EXPAN systems as the LVL manufacturer is considered to be the key company. Moreover, as outlined earlier, raw material acquisition is excluded from the scope of this research and will not be included in the model. The level of detail for the model will be focused on the manufacturer, designer (structural engineer), fabricator and installation. This focus was established through interview results in Chapter 6, which highlighted these stages in the supply chain had the biggest affect on the performance of prefabricated timber systems. The model will focus on the relationship between these stages and how they can be best arranged to address the issues highlighted in interviews and to meet the needs and expectations of customers (head contractor and clients) in the non-residential market.

7.6.4 Fourth step – define supply chain configuration

The fourth step of the framework outlines the supply chain configuration in the model. It shows clearly which company along the supply chain is responsible for each process (ownership decisions) and the relationships between members in the supply chain. This addresses the three main goals of the supply chain model. As outlined in Table 7-3, supply chain performance measures (metrics) associated with model goals data from interviews; industry analysis (Porter's five forces analysis); and strategic procurement literature will be used to develop the model. Following structural contingency theory, the structure of the supply chain will be modelled in such a way as to meet the requirements of the non-residential construction environment. These needs and expectations are outlined in section 7.3 above (market needs and expectations).

As previously outlined and highlighted in Chapter 6, the current supply chain for prefabricated timber systems in Australia and NZ is fragmented with little communication or integration between supply chain members. One of the key goals of this supply chain model, therefore, is to develop a supply chain configuration that will address the issues highlighted in chapter 6, in particular fragmentation, lack of communication and meeting the market needs and expectations of the non-residential environment. The model will also endeavour to provide a single point of contact for head contractors from a financially stable entity, providing both a supply and install service. Prior to outlining the supply chain model configuration the relevance of strategic procurement in SCM will be reiterated and then adopted to support the development of the model.

One of the most revolutionary changes over the past decade to affect the strategic management of supply chains is the rethinking of organisational structure to suit the demands of the market (Christopher 2011). In order to respond to market demands, organisations have restructured and a new form of organisation has emerged, where the supply chain is used as an extension of the organisation. When applying structural contingency theory to supply chains it is suggested that the individual dimensions of the supply chain should be aligned in order to achieve the best fit for a particular environment. SCM initiatives such as partnering, strategic alliances, and joint ventures can be adopted to integrate the supply chain with the primary goal of increasing value for the end customer through achieving time and cost savings and quality improvements. There is growing evidence to suggest that supply chain integration can have a positive impact on operational performance outcomes such as delivery times, cost and quality (Droge, Jayaram & Vickery 2004; Flynn, Huo & Zhao 2010; Rosenzweig, Roth & Dean 2003).

Partnering and the creation of strategic alliances could be used as a strategy for the prefabricated timber supply chain in Australia and NZ. This could help drive time and cost efficiencies and better meet the needs and expectations of customers – both head contractors and clients. Integration offers the opportunity to achieve the closeness and co-ordination similar to vertical integration without having to outlay significant capital investments (Beach, Webster & Campbell 2005). As outlined in Chapter 6, prefabricated timber ETO companies in Europe have vertically integrated models, though their market situation is different, being more mature, with higher demand and acceptance for prefabricated timber systems. Large capital costs are typically required for vertical integration and this strategy is typically most suited to stable and mature environments (Harrigan, 1984). In Australia and NZ the market for prefabricated timber systems is still in its infancy: 'the idea of vertical integration is anathema to an increasing number of companies. Most of yesterdays highly integrated giants are working overtime at splitting into more manageable, energetic units – i.e. de-integrating. Then they are turning around and re-integrating – not by acquisitions but via alliances with all sorts of partners of all shapes and sizes' (Grant 2007). Using these ideas as a base there is the possibility of adopting strategic procurement strategies between a number of firms in the ETO supply chain to offer an integrated 'solutions approach' for prefabricated timber systems such that the supply chain is an extension of the organisation.

Partnerships and alliances between manufacturers, fabricators, designers and installers could streamline the current fragmented supply chain and help minimise waste and delays. SCM literature typically limits supply chain integration to suppliers, although for ETO products the decoupling point is located at the design stage, so each customer order penetrates the design phase of a product (Gosling & Naim 2009). For prefabricated timber systems it is important that the design team, in particular the structural engineer, has a close relationship with manufacturers and fabricators in order to obtain a better appreciation for each other's challenges/problems, and capabilities. This collaboration will help drive better building designs and increased value to clients.

Using the data gathered in this thesis to date, the supply chain model in this thesis will be outlined in the following section. The model is termed specialist business entity (SBE) and has a number of designers, fabricators and installers under its umbrella. The SBE is a group of businesses and these businesses form a network through strategic alliances and partnerships. This would facilitate the necessary resources to undertake a number of projects at the same time. This capacity would still be relatively limited in the short term though it is envisaged that it would grow as demand increased. Strong project management skills from the lead entity would be required.

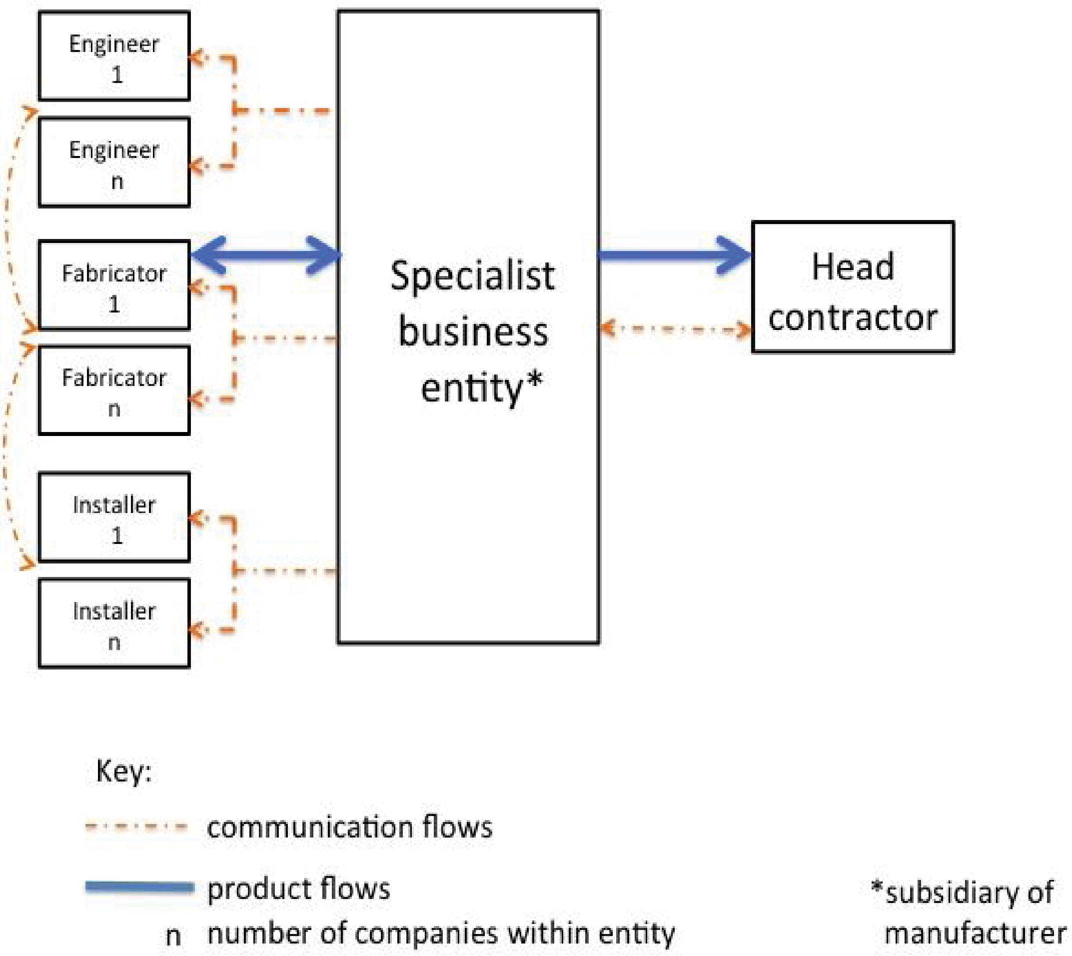

Figure 7.4 Supply chain model for prefabricated timber systems in Australia and NZ

The SBE will provide a single point of responsibility to the head contractor; this is a common expectation in the commercial construction market. The SBE will provide supply of LVL or CLT panels to the fabricator(s) as well as provide Project Management (PM) services for the design, fabrication and installation to the head contractor which will allow prefabricated structural systems to be delivered in a 'supply and install' contract. A key aspect of the model will be that the SBE will be in charge of liaising with the head contractor. Another key feature is that the SBE is a subsidiary of a large manufacturer e.g. LVL or CLT. It is important the SBE is a subsidiary to and have the brand backing of a large shareholder (the manufacturer of LVL or CLT), and even if it were at arm's length to the shareholder, this would provide some financial certainty to the head contractor, knowing that it has this backing. As outlined in the Porter's five forces analysis, the manufacturer is a powerful supplier who can dictate the price of LVL. The LVL is a key input into the prefabricated timber systems, which makes up a high percentage of costs. Being able to control this cost will allow the manufacturer to determine, if it is trying to win a particular project it bids on, whether it can set the price of the component input whilst keeping it confidential to the market. Moreover, always being able to supply components directly to the fabricator and not through a distributor will help save costs.

The sequence of communication along the supply chain model will be as follows. Firstly the SBE will undertake business development work for new projects. When projects arise the SBE can consult a fabricator, designer and installer that is closest to the project. Ideally, within the SBE network there will be a number of fabricators in different locations such as Sydney and Melbourne. This will allow these companies to be close to the project site. Currently this may pose an issue as there are limited fabricators, installers and designers in all locations though as time progresses and demand increases more of these companies will enter the market. There is also potential to engage frame and truss manufacturers to assist with the fabrication process, in particular floor systems.

When tendering on a project with head contractors, the SBE will directly contact engineers, fabricator and installers to assist with the tender and submit this as a 'supply and install' package to the head contractor. This tender will also outline the SBE team and which will be the companies that will work together to deliver the product if the tender is won. If the SBE wins the tender, the engineers will work with the fabrication company to design, detail and then fabricate the most cost efficient system. Having these companies working together from the outset, particularly with the engineer being acutely aware of the fabricator's capacity, is important. The manufacturing entity in the SBE will supply components (LVL) to the fabrication company. When the design and fabrication has been completed the installer will be engaged to install the system on site. The SBE will project manage this installation process.

7.6.5 Fifth step – characterise supply chain model elements

The final step in the modelling process is to finalise the model elements and reiterate how the model is able to achieve the goals outlined in the second step of the framework. The interviews in Chapter 6 highlighted a number of key issues in the industry. This model has potential to address these issues as follows. *Fragmentation* & *Communication* will be addressed, as the SBE will create business networks between key parties in the supply chain to tender and deliver projects. The companies in the SBE aren't involved in an exclusive arrangement and companies can work on projects outside the SBE, though as demand increases it is envisaged that the SBE will provide enough work to support all the members in the network. As the members work together over and over on a number of projects through a partnership/alliance scenario they should develop a close bond and support one another.

Fabrication capacity was the key issue highlighted and whilst this SBE model will not directly increase fabrication capacity it will provide an avenue for business development that fabrication companies on their own traditionally lacked. This will potentially help obtain more projects and demand, which should provide the scenario for capital investments to make the process more time and cost efficient. Moreover, there is potential for the manufacturer to vertically integrate into the fabrication space – though until market demand increases this isn't preferred (Harrigan 1994). In a similar scenario to the limited capacity in *fabrication,* this model will not directly increase capacity at the outset. These interviews highlighted that this lack of *Design detailing* and *Installation* was generic throughout the industry as a whole. There are a number of engineers and installers with expertise and it is a matter of ensuring these companies are part of the SBE at the outset. Then as demand increases and more projects come up, experience and expertise will follow.

This model has a number of advantages that have the potential to achieve time, cost and quality benefits. Firstly it uses a cheap efficient way to create an integrated supply with little capital investment, particularly whilst the market demand for these products is in its infancy. The new start up entity, whilst only requiring minimal capital investment, still has overheads that will need to be recovered such as resources to undertake project management work and business development. Through the business networks it is able to use subcontractors' insurances. The SBE can enhance delivery schedules by organising construction programs, design freeze points and payment schedules as well as generally saving time for the project and subcontractors as a whole. Having a number of engineers, fabricators and installers under the umbrella of the entity can help with flexibility and the ability to match resources to projects where necessary. Some potential issues with the model that would need to be addressed in practice include the selection of alliance members, so important to obtaining head contractor and client confidence. The financial structure needs to be considered also to prevent the lead entity introducing competitive pricing between its fabricators, designers etc. This could result in adversarial relationships within the SBE and be a disincentive to others joining and as well as resulting in partners being less willing to share knowledge and resources.

7.7 Conclusion

Through a top-down approach using structural contingency theory the supply chain model known as an SBE has been developed. As outlined the model has been developed to address issues highlighted in interviews as well as better meeting the needs and expectations of customers (head contractors and clients) in the non-residential construction market. This model has also used SCM literature, in particular strategic procurement literature, to support its development. The overall goal of the model was to change the structure of the supply chain to better suit the environment in the non-residential construction market with the end goal helping improve the performance (time, cost and quality) of prefabricated timber systems in Australia and NZ.

All this leads into Chapter 8 where the model and in turn structural contingency theory will be tested in relation to prefabricated timber systems in an Australian and NZ context. The aim is to test structural contingency theory in relation to prefabricated timber systems. With the hypothesis developed from structural contingency theory – that unless ETO companies involved in the production and delivery of prefabricated timber systems in Australia and NZ change their structures to suit the non-residential environment and better meet the needs and expectations of customers in this market, performance will be low and a number of issues in relation to time, cost and quality will occur.

Chapter 8 Building case studies & theory testing

8.1 Introduction

This chapter presents the findings from three building case studies – two in NZ and one in Australia. Following on from chapter 7 these case studies will be used to test the structural contingency theory and in turn the supply chain model developed in chapter 7. The ideas behind structural contingency theory were used as a basis when developing the supply chain model. If the case studies confirm the structural contingency theory, this chapter will also support and validate the supply chain model. Following the case studies Chapter 9 will outline how the model can be implemented in practice. Three case studies have been used:

- Case study 1 – UTS floor systems, Sydney, Australia
- Case study 2 – STIC office, Christchurch, NZ
- Case study 3 – NMIT, Nelson, NZ

The case studies flow on from one another and increase in project size and complexity. Details on why these case studies were chosen were covered in chapter 5. In each of the case studies, a short introduction into the project is provided, outlining its location, context and the prefabricated timber systems used. The supply chain of the prefabricated timber systems is also mapped for each project. As aforementioned these case studies have been undertaken to examine issues along the supply chain that affect the performance of prefabricated timber systems. This chapter intends to follow on from and to confirm the case study findings in chapter 6 as well as to establish any further issues along the supply chain. Data collection methods from these case studies include *documentation, interviews* and *direct observation.* Site visits were undertaken to these building case studies. During these site visits interviews were undertaken with project participants. Direct observations and documentation were also collected from the project sites. Visits were also undertaken to manufacturing and fabrication facilities involved in the projects.

Similar to site visits interviews, documentation and direct observations were obtained from visits to these manufacturing and fabrication companies.

The aim of this data collection was to obtain details on the issues along the supply chain that specifically impacted on time, cost and quality and, in particular, to establish how these issues were affected/caused by the structures (business models) of the organisations along the supply chain. Pattern matching is used to analyse the case study data and a seven-step framework developed by Hak & Dul (2009b) to test theories from case studies is adopted for each case study. This framework is used to test structural contingency theory in relation to the supply chain for prefabricated timber systems. The scope of the supply chain activities varies slightly in the case studies. This scope was primarily governed on the data available on the different projects.

Case study 1 – manufacturing, fabrication & logistics/transportation

Case study 2 – manufacturing, fabrication, installation & logistics/transportation

Case study 3 – design, manufacturing, fabrication, installation & logistics/transportation

8.2 Case study 1 - University of Technology (UTS) floor systems, Sydney, Australia

8.2.1 Introduction

This case study focuses on the floor systems used as part of the structural and acoustic testing requirements for the Structural Timber Innovation Company (STIC) at UTS. In 2010 a total of eighteen floor systems were fabricated by a specialist fabricator in Melbourne, Australia and then delivered to UTS, Sydney. These were the first prefabricated floors of this nature in Australia, so it is important to learn from the negative issues that occurred along the supply chain of these systems so they aren't repeated. Figure 8.1 shows the prefabricated floor systems completed in the fabrication workshop. There have been no applications of these systems in Australia in multi-storey buildings, so unfortunately analysing data from prefabricated timber systems of this nature in a completed building in Australia wasn't available at the time of this research. Case studies 2 – 3 will analyse prefabricated timber structural systems in multi-storey non-residential buildings in a NZ context.

Figure 8.1 Completed prefabricated floor systems

Data collected from this case study includes *documentation, interviews* and *direct observation.* Interviews were conducted with four key project members from the same company and details are outlined in Table 8-1 below.

Table 8-1 Interviewee details UTS floors

Interviewee	Company Type	Country	Work Experience
General manager 1	Fabrication	Australia	20 + years
Director 1	Fabrication	Australia	20 + years
Engineer 1	Fabrication	Australia	10 - 20 years
Workshop hand	Fabrication	Australia	20 + years

These interviews were conducted during a two-day visit to the fabrication workshop. The purpose of these interviews was to discuss key issues that occurred in relation to time, cost and quality. During this visit *direct observations* of any issues during the fabrication process were also made and documented with notes. Time taken to fabricate systems and the factors affecting the time of fabrication were also documented. *Documentation* from the project was also obtained, including cost details, program details, CAD drawings and details.

The two key companies studied in this case study were an LVL manufacturer (Manufacturer 1) and a specialist fabricator (Fabricator 1). Manufacturer 1 supplied the LVL for the floor systems from its manufacturing plant in NZ. This plant covers more than two hectares in floor space and has the capacity to produce 400m^3 of LVL per day. LVL billets are typically supplied 1220 or 610mm in width (the extra 10/20 mm is to allow for saw cuts). Lengths are primarily governed by transportation capacity - 12 or 13m are the typical length though they can be up to 18m.

Figure 8.2 below outlines the supply chain for the prefabricated timber flooring systems. In this supply chain, design and shop drawings occur at the same time as manufacturing of billets occurs. In this case study, however, and following on from details set out above, due to the small quantity of material it would have been manufactured faster than design and shop drawings could be completed. Fabricator 1 is a specialist timber fabricator focusing on the development and fabrication of LVL based building systems and components. They have been in operation for more than 20 years and are based in Melbourne, Australia. They specialise in engineered timber and recently have invested in a number of software and machinery technologies, including building information modelling (BIM), which allows effective collaboration with engineers and other design consultants.

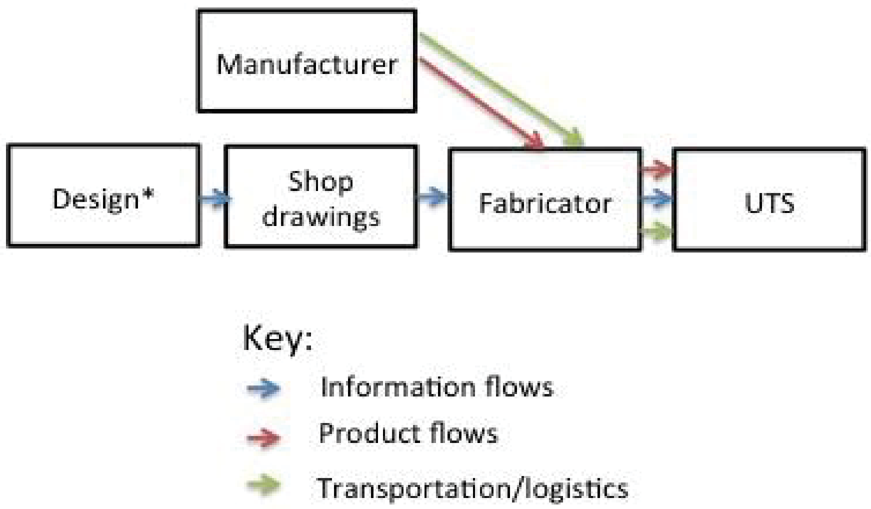

Figure 8.2 Supply chain for prefabricated timber elements on project

* In this particular case study, design was a collaboration of sorts between UTS and Fabricator 1. The design and shop drawings for the floor systems were originally created by an engineer at UTS and then were sent through and finalised by fabricator 1 – who has in-house design expertise. This is an unusual supply chain as these prefabricated timber systems were used as test specimens as part of the STIC research-testing program at UTS.

8.2.2 Key issues affecting performance (time, cost and quality)

The key issues affecting time, cost and quality along the supply chain of this case study are detailed below.

TIME ISSUES

- Manufacturer 1 supplies material three months late to Fabricator 1.

The LVL supply from Manufacturer 1 was imported from NZ, which resulted in a number of issues occurring along the supply chain. Firstly, the LVL components (billets) were scheduled to arrive at the fabricator in December 2010, though didn't end up reaching Melbourne until March 2011. This delay has been attributed to issues at shipping docks in NZ and logistics problems associated with the LVL manufacturer. General Manager 1, from Fabricator 1, explained how at times employees from Manufacturer 1 focused primarily on reaching their key performance indicators (KPIs) in relation to volumes of timber supplied measured in cubic metres (m^3). They typically don't have much involvement once materials leave the manufacturing plant; once the LVL has left the manufacturing plant it is no longer their issue.

The issue is that if the logistics people at Manufacturer 1 aren't in communication with the shipping companies/dock management in NZ or, even worse, aren't interested in what happens to the LVL once it leaves the plant, billets may not obtain priority at the docks and fail to load onto ships in a timely fashion. If the billets arrive early at the docks they run the risk of sitting at the back of the queue because material placed in front of them gets loaded first onto ships. If this happens, the billets can potentially miss out and not get loaded onto the next ship from NZ to Australia. If there were better communication links with the logistics team at Manufacturer 1 and the docks there would have been a greater potential for components to get onto ships earlier.

- Fabrication process for initial floor systems takes significantly longer as a jig/template has to be set up. Until a number of generic flooring systems are developed a lot of manual labour and time will be needed, resulting in high costs.

Whilst visiting Fabricator 1, times were recorded for the fabrication of each system. It was noted that the initial floor system took significantly longer to fabricate, as a jig had to be set up to help facilitate a more efficient process for the following systems. The first floor system took close to 2 hours, then subsequent floor systems on average 1 hour. Once the jig was finalised the rest of the floor systems were calculated to take on average 40 mins each. The major issue with the fabrication stage in the supply chain as demonstrated in this case study is that the process is highly labour dependant, with 4 – 5 staff involved in the fabrication of each floor system. Computer Numerical Cutting (CNC) machinery does help to some extent with time efficiency, though it assists more with quality than efficiency. Director 1 from Fabricator 1 mentioned it was feasible to fabricate each system in 30 mins, and as the fabrication staff became more efficient this sounds achievable. As much as this is a supply chain issue, it is also related to supply and demand in the market. Since the demand for engineered timber is limited, automation doesn't seem to be relevant and a labour intensive process is quite an obvious outcome. It will bring better value for money from mechanisation if demand increases.

COST ISSUES

- Even though CNC machinery is used, a lot of manual labour is required to fabricate floor systems.

Fabricator 1 does have some degree of automation in the fabrication process compared to the glulam manufacturers, though in essence their fabrication process is still relatively primitive and labour intensive. Once again this primitive fabrication process is market driven and until demand increases supply capacity will be limited. This does highlight that the capacity of the fabrication stage in the supply chain is overall one of the key issues that affects time, cost and quality of prefabricated timber systems. CNC machinery currently allows a design to be created in CAD work or similar software and then transferred to the CNC machine. The CNC machine allows a fully automated process that cuts members, pre-drills them and so on, with computer-controlled accuracy. It is important to note for the UTS floor systems and prefabricated timber beams and columns, all the CNC machine is doing is essentially marking out positions of screws and then pre-drilling members. The machine has the potential to cut/rip elements to varying widths, though being a large table it can be a much more efficient machine for cutting and ripping billets.

Once the different members of the floor systems (i.e. flanges and webs) have been processed by the CNC machine they then have to be screwed and glued together. Fabricating LVL components together (through screwing and gluing) is generally done through manual labour and this high amount of labour is reflected in the overall costs. Labour makes up a significant percentage of overall fabrication costs – approximately 53%. This percentage was determined through recording the time taken to fabricate each floor systems and relating these times to Figure 8.3. Director 1 from Fabricator 1 admitted that he is aware that a high amount of labour is required to fabricate the systems, though as there currently isn't a large demand to mass produce these systems, it is currently not feasible to spend the capital costs necessary to develop a fully automated process.

This process of screwing and gluing beam elements together was highly labour intensive and it was one of the major issues in the fabrication process affecting time and costs. Labour is an expensive input and is typically far less efficient than automated machinery. A possible alternative could be nailing elements together or to install capital that can efficiently screw/nail and glue elements together. Table 8-2 below outlines a break up of the costs of the UTS floor systems. (1) As can be seen freight makes up close to 10% of costs (2) though also a relatively significant amount of time (3) where the transportation of materials from the manufacturing plant to the fabrication workshop and then from the fabricator to UTS (4) involves a lot of double handling and isn't the most efficient process possible.

In this case after they left the fabricators' workshop they went to a depot in Melbourne and were then transported to a depot in Sydney where they awaited distribution to UTS. The entire process took approximately 3 days. General Manager 1 from Fabricator 1 explained: 'Nobody in freight wants to hear about timber, as it typically isn't on pallets and is difficult to load/unload onto trucks.' This leads to higher costs and longer time to transport.

Table 8-2 Total costs of the UTS floor systems

Items	**Cost ($)**	
Procurement of materials and fabrication of floor panels and test specimens for testing under the STIC program		22,000.00
Freight		1,980.00
	Sub-total	23,980.00
	GST	2,398.00
	Total due including GST	26,378.00

Source*:* Tax Invoice from Fabricator – March 2011

In total there were 18 systems delivered to UTS, which consisted of

<u>TOTAL cost (including GST)</u> = $3,278 per m^3

= $3,006 per m^3 (excluding freight)

or

= $334 per m^2

= $306 per m^2 (excluding freight)

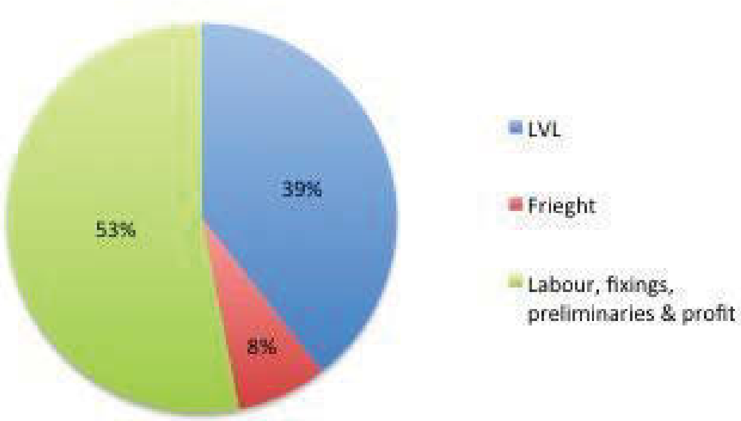

Figure 8.3 UTS test floors break up – Expressed as percentage (%) of total cost

*Based on LVL at a rate of $1,300m^3 as quoted by fabricator 1.

The UTS floor systems have been designed with a 600mm top flange, though it could be more economical over a complete floor plate of a building to process a standard 1200mm wide LVL billet for the top flange. If the current UTS floor system design was to be used in an actual building it would require twice as much crane time as a 1200mm wide floor system and there would be twice as many floor systems. The fabrication process would potentially be faster also and it could potentially result in 3 webs over 1200mm instead of 4 over 2 x 600mm elements, which would lead to material savings. The fabricator mentioned that their K2 CNC machine is only capable of processing a maximum width of 625mm so I assume this was a governing factor in the design. LVL manufacturers in Australia and NZ are also all capable of producing max 1200mm wide billets though in Finland a manufacturer produces an LVL product called Kerto-Q, which can be produced up to 2500mm in width. Provided an adequate structural design could be developed if floor panels could be developed at a width of 2400mm this could potentially lead to even more efficiencies over the fabrication and in-situ erection process. Another option could be using CLT as the top flange for the floor systems.

QUALITY ISSUES

- Timber systems left out in rain during transportation lead to components arriving at fabrication workshop damaged (cupped)

During the transportation process from the manufacturer to the fabricator, not only were components delayed, but the LVL billet was left exposed to the weather on the shipping docks. When the LVL billets finally arrived at the fabrication workshop 3 months late they had experienced severe cupping. To address this issue the billets had to be flat stacked to help reduce the cupping and mitigate the effects from water damage. General Manager 1 from Fabricator 1 noted that 'Plastic covers used by manufacturer 1 to protect the LVL billets are of an inferior quality compared to plastic covering used in the USA.' Better quality plastic covers, even though they may be more expensive, are a small price to pay if it prevents the time and cost of having to fix the damaged components or, even worse, if they are beyond repair, to wait for replacement components to be delivered.

This is a particularly large issue that needs to be addressed for larger multi-storey non-residential projects. It is imperative the logistics process is optimised to ensure the timber systems aren't left out on-site where it has the potential to get wet, affected by sun and so on. If timber systems are damaged during transportation to site or whilst on-site awaiting installation it could result in devastating impacts on a projects program – as the structural package is typically a critical path item. Being on the critical path means they are tasks that determine the end date in a project schedule and if one of those tasks is late, then the project end date will have to be extended. Running over time can also potentially lead to liquidated damages, so an efficient transportation network that ensures elements can arrive on time and without any damage is something that needs be looked at in greater detail.

8.2.3 Case study analysis and theory testing

Hak & Dul (2009b) expound that the methodology of theory testing from case studies involves seven steps. This research adopts these seven steps as a framework. The UTS floor system case study is analysed through the use of these steps to test structural contingency theory in relation to the supply chain for prefabricated timber systems. Reasoning for use of these steps and pattern matching are covered in detail in Section 5.5.4 of Chapter 5. For this analysis steps 1, 2 and 3 are generic for all case studies and are covered in detail in Section 5.5.4 so they were not repeated here – instead the analysis will begin at step 4.

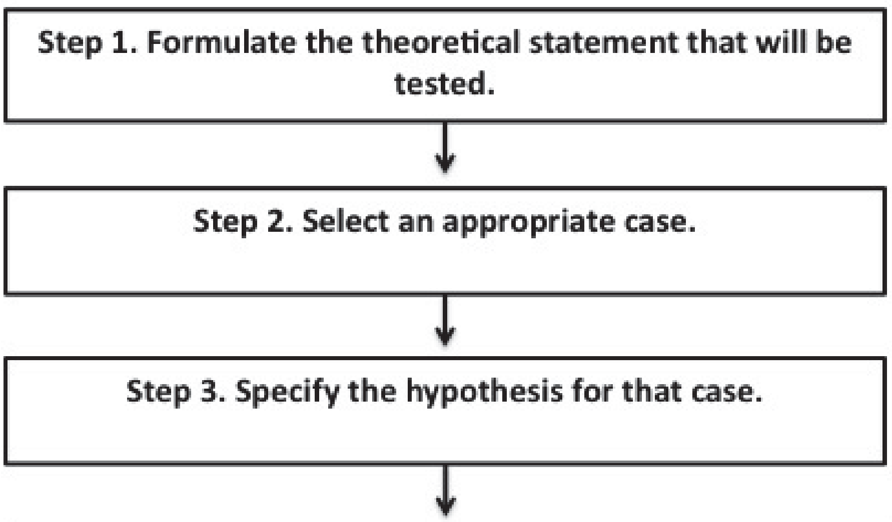

Figure 8.4 Theory testing from case studies

Step 4. Measure the relevant variables.

Criteria for valid and reliable measurement are the same for any type of research strategy, be it a survey, an experiment, a case study, or another theory-testing research strategy. In the case study, evidence is obtained through interviews, documentation and personal observations. Measurement entails determining whether X is present and whether Y is present. In this research X is related to instances where there is a lack of integration in the supply chain and where it is not structured in a way that best suits the non-residential environment. Y refers to cost, time and quality issues along the supply chain. The result of this measurement is the observed pattern.

Step 5. Test the hypothesis.

Testing consists of comparing the observed pattern with the expected pattern. The expected pattern is outlined in detail in step 3 (Refer to Section 5.5.4 Chapter 5 for details). In the observed pattern, Manufacturer 1 in this case study predominantly supplies LVL material to the residential construction market. They generally have little communication or involvement with downstream suppliers (either fabricator or head contractor). Fabricator 1 is a small job shop organization that has limited design and detailing expertise. They do not offer installation services. Issues that occurred on the UTS floor system case study and how the organizational and supply chain structure affected these issues is covered below.

In the non-residential market in Australia and NZ other ETO products such as steel and prefabricated concrete offer head contractors and clients a complete solution. Manufacturing, fabrication, design and detailing and installation are offered in a complete package. If a similar scenario were offered in this case study the three-month delay in supply of material from the manufacturer to fabricator would likely not have occurred, as there would have been more communication between the manufacturer and the fabricator. This lack of communication is due to fragmentation along the supply chain. In Europe where ETO timber companies are vertically integrated downstream from the manufacturing stage to installation of systems on-site these communication issues are less of a problem.

This lack of communication between organisations (Manufacturer 1 and Fabricator 1) along the supply chain also leads to issues impacting the quality of products. Timber systems were left out in rain during transportation, which lead to components arriving at fabrication workshop damaged (cupped). This occurred, as the manufacturer didn’t have any involvement with the materials once it left their manufacturing facility. If Manufacturer 1 had more involvement downstream not only with Fabricator 1 but also with the head contractor, it would be more in their interests to ensure products that leave their facilities are tracked and monitored. One of the expected patterns is that when the supply chain is fragmented and companies have little communication or collaboration with one another time, cost and quality issues are expected to occur. The observed patterns from this case study supported and matched this expected pattern. There was a lack of communication present, in particular between the manufacturer and fabricator, which resulted in a number of time and quality issues outlined earlier.

Size of the company is an important contingency, where Fabricator 1 is a small job shop set up to deliver prefabricated timber systems to the residential and smaller non-residential projects. In order to be more competitive and better suit the needs of the larger projects in the non-residential market, Fabricator 1 should increase in size. This would allow them to produce prefabricated timber systems more efficiently as well as allowing greater amounts of storage. Developing a more automated process would negate the need to take significant amounts of time setting up a jig/template. Moreover, the more automated the process becomes the less cost intensive labour will be needed. The high amount of labour also leads to higher costs. Even though computer numerical cutting (CNC) machinery is used is the fabrication process in the UTS floors, it is still labour intensive. Manufacturer 1, even though it is a large company compared to Fabricator 1, is predominantly set up to deliver commodity products for the non-residential market. It generally has limited direct communication or involvement in the supply chain downstream.

Another expected pattern as outlined in section 5.5.4 of chapter 5 is that when companies along the supply chain are structured to suit the residential market and not the non-residential market (which has different market needs and expectations - see section 7.3 of chapter 7) it is expected that time, cost and quality issues will occur as a result. The observed patterns from this case study supported and matched this expected pattern, where it was established that Manufacturer 1 is predominantly structured to deliver products for the residential market and Fabricator 1, even though it has skills and expertise to deliver products to the non residential market, lacks the size and scale to cost and time to efficiently deliver structural systems competitively in the non-residential market.

Step 6. Formulate the test result.

'The test result is either a *disconfirmation* of the hypothesis or a *confirmation*' (Hak and Dul 2009b p. 8). From the data collected in the case study through *interviews, documentation* and *personal observation* and analysed in step 5 above the hypothesis is supported when condition X is present (supply chain isn't structured in a way that best meets the needs and expectations of the environment i.e. lack of integration and communication) and outcome Y is also present, with outcome Y relating to time, cost and quality issues occurring as a result of condition X. Thus, organizational structures that don't suit the environment and lack of integration along the supply chain result in a number of performance issues (time, cost and quality) for prefabricated timber systems.

Step 7. Formulate the implications of the test result for the theory.

'Conclusions about the robustness of a theoretical statement cannot be drawn on the basis of just one test, but only after a series of tests. Hence, discussing the implications of a test result always implies comparing the result with those of earlier tests in a series of replications' (Hak and Dul 2009b p. 8). The UTS floor systems are the first case study in part two of this research to test and confirm structural contingency theory in relation to the supply chain for prefabricated timber systems. The following two case studies will also undergo these seven steps to test the theory.

8.2.4 Conclusion

The UTS floor systems case study highlighted a number of time, cost and quality issues that occur along the supply chain. It was confirmed that these observed issues occurred due to a number of reasons, including lack of communication and collaboration amongst supply chain members, and companies along the supply chain being predominantly structured to suit the residential market and not the non-residential market. Through the use of the seven-step framework, structural contingency theory was tested and confirmed for this particular case study - as the expected patterns and observed patterns matched.

8.3 Case study 2 STIC office, Christchurch, NZ

8.3.1 Introduction

Following on from case study 1, this section intends to establish the key issues that affect performance (time, cost and quality) along the supply chain on another project. It also aims to establish how the organisations along the supply chain impact on the performance of prefabricated timber systems. This case study focuses on the STIC office at the University of Canterbury in Christchurch, NZ. The prefabricated timber systems for the project were originally used for testing in the University of Canterbury's laboratory as part of research for the Structural Timber Innovation Company (STIC). The structure was dismantled and slight modifications were made to allow the structure to be reconstructed on campus at the University of Canterbury. It is now used as the official head office of STIC. Figure 8.5 below shows some photos of the STIC office during construction.

Figure 8.5 STIC office during construction

Source: Smith, Holmes & Carradine (2012)

This particular project had a unique supply chain, where the prefabricated timber systems were originally fabricated for testing at the University of Canterbury. Then after testing was complete the decision was made to deconstruct the test structure (shown in Figure 8.6) and, after minor modifications, reconstruct it as the STIC office on the campus at the University of Canterbury.

Figure 8.6 STIC office in University of Canterbury test laboratory

Source: (Newcombe, Pampanin & Buchanan 2010a)

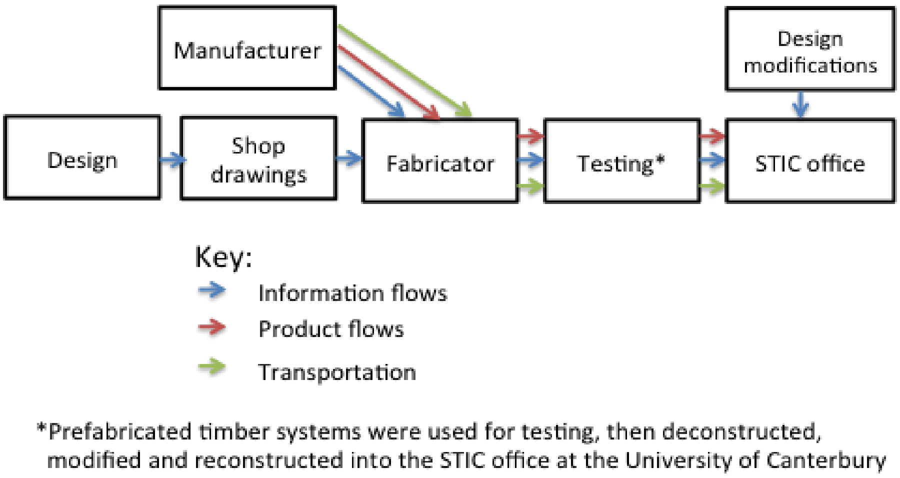

Figure 8.7 Supply chain for prefabricated timber elements on the project

Figure 8.7 depicts the supply chain for the prefabricated timber systems for the STIC office. As stated it is unique in that the prefabricated structural system was constructed for testing and then deconstructed and reconstructed into the STIC office. This case study will focus on the issues that affect time, cost and quality as if it were the supply chain for a typical office structure. The issues involved in the installation and deconstruction of the test structure were not considered. The focus will be on the manufacturing, fabrication and final installation of the STIC office. The minor modifications made to the structure have also been left out of this study.

Data collected from this case study includes *interview, documentation* and *direct observation.* An interview was conducted with a key project member from the project. The interviewee was a Construction Manager (Construction Manager 1) who worked for the head contractor responsible for the final installation of the structure. The interviewee has 20 + years' work experience on a range of different projects including, residential, commercial and industrial. Due to geographical limitations this interview was undertaken in person by a colleague from STIC in NZ. The list of semi-structured questions was developed and used for the interview and the findings were written up and analysed. *Documentation* from the project was also obtained, including costing and program details. The following analysis of issues comes from a combination of primary data from interviews, direct personal observations and documentation.

8.3.2 Key issues affecting performance (time, cost and quality)

The key issues affecting time, cost and quality have been established from an *interview* with the construction manager involved in the project. *Documentation* on costing and further details of the project were also used. Although the project was successful, some issues and recommendations were noted by the construction manager during the erection of the frame. The focus of this feedback from the project was limited to the prefabricated timber structural components used on the project, including frames (beams & columns), walls and floor systems. This was the first time the 'balloon frame' method was adopted for this construction type. Balloon frame construction is where structural frames and columns span more than one floor height (see Figure 8.5). Balloon frame construction is also different from platform construction where each column is only one single floor height.

TIME ISSUES

- Installation of prefabricated timber systems

Preassembly of frame

The building consisted of two frames, which were preassembled and then craned into the place – this was done to maximise time savings on-site. The first frame was preassembled on the plywood floor of the office structure and the second frame was assembled on the grass area to the side of the structure. The second frame was assembled on the ground next to the structure in order to keep the workmen busy and to allow a number of tasks to occur simultaneously – helping to increase productivity. Construction Manager 1 outlined that on a more restricted site that didn't have the luxury of extra space around the building footprint, frames could be preassembled and stacked on one another. Where upper level frames would be preassembled first and in turn be on the bottom of the stack, the lower level frames on the top of the stack could be installed into place first. On this particular site, frames weren't preassembled and stacked on top of each other due to concerns of overloading the timber floor. On a site with a concrete ground floor these concerns would not present such an issue.

Installation of frames

A Hiab truck was used for all lifting on-site. The benefit of using a Hiab is that a driver/operator is provided and for a project of this scale it is deemed to be a very economical way of lifting prefabricated units. If a crane were to be used a team of at least three would be required, which would significantly increase costs. For the installation of the frames,

Figure 8.8 Temporary plywood gussets (non-engineered)

strops were used to lift and move the frames into place on the concrete plinths. There were no predetermined lifting points on the frames and feedback advised that the installation process would have been significantly easier and safer if there were predetermined lifting points in place. Having to rely solely on the strops meant the project team was concerned about the possibility of the supports slipping and the frame potentially dropping during the lift. In order to alleviate this issue during the project, temporary plywood gussets (non-engineered) shown in Figure 8.8 were installed on the frames to help increase the out-of-plane rigidity during loading. Construction Manager 1 outlined using predetermined lifting points similar to those used in precast concrete would have saved time on site and lead to a safer lifting process.

The second frame was installed significantly faster than the first frame. This occurred due to issues with hole tolerances when installing the columns onto the steel rods on the concrete plinths. As shown below in Figure 8.9, having to line up the four holes in the base of the columns with the steel rods, over the length of each frame (twelve holes) at the same time caused issues onsite. Construction Manager 1 stated that key issues were the length of the bars, welding onsite and only a 2mm tolerance around the bars. A significant amount of time was lost on one frame that didn't sit properly on the bars. Overall, even though there were a number of issues, the project went smoothly, which was attributed to the quality of the senior tradesman on this project. Construction Manager 1 did outline that on a larger scale project this particular connection detail (Figure 8.9) would potentially cause significant issues.

Propping/bracing of frames and floors

The frames were propped using traditional adjustable propping, similar to those used for tilt-up concrete construction. On this particular site the propping was done around the perimeter of

Figure 8.9 Installing frames onto steel rods on concrete plinths

the structure. On a project that didn't have the space around the building, propping could be done internally and then removed as the floor units were installed. As the floors were precast units no temporary propping was needed beneath them. This equated to time savings on site, as if the concrete was to poured in-situ the floors would need to be propped for at least one week. Moreover, as the frames were preassembled on the ground and then lifted into position, limited bracing was needed, resulting in time and cost savings.

Fabrication for these building elements was performed by a company which has a core business focus on manufacturing glulam. They also undertake fabrication work on the side, however, using the same presses and machinery used to manufacture glulam. This capital equipment requires a lot of labour to operate with very little automation. In turns, this results in a relatively long and slow fabrication process, which results in increased costs. This aspect of the fabrication process in the supply chain is covered in further detail in the costs section below. Similar to case study 1, the fabrication process is a key stage in the supply chain that leads to a number of issues that affects time, cost and quality.

Overall key issues and lessons learned regarding time

A lot of the key issues affecting time covered in this section were from the installation stage in the supply chain. However, as covered at the end, the fabrication stage was also a key issue that not only can affect time but also costs – this is covered in the section below. From the project, one key thing to achieve time savings is to use a balloon method of construction and pre-assemble the frames on the ground and then lift them into place. Construction Manager 1 believed that it is potentially two to four times faster to do this than to install columns and beams individually. When installing prefabricated systems on-site, a Hiab would need to be used whether elements are installed as a complete frame or individually, as each member is too heavy to lift by hand. On a larger project with larger frames, a permanent crane would most probably be required. There are also benefits of installing completely prefabricated TCC floor units as opposed to installing timber floor units and then laying steel mesh and pouring concrete in-situ. The added benefit of having completely prefabricated floor units is that propping isn't required under the floors for at least one week.

Another key lesson learned from the project was that, if predetermined lifting points were installed on the frames and a simpler connection between the columns and the concrete plinth was used, further time savings could have been achieved. Construction Manager 1 observed that the key to time savings on-site is high levels of prefabrication. The more work done off-site the better. Ideally complete frames or wall systems could be pre-assembled in the fabrication workshop or alternatively, in a major city, an intermediate assembly operation could be set up in a warehouse to pre-assemble the frames. The main potential limiting factor for this idea would be transport related.

COST ISSUES

- Overall costs of the building

The final cost of the STIC office structure was $NZD 290,700, which included the $NZD 53,000 cost for the original structure. Whilst it would be good to provide a comparison between estimated costs for the structure and actual as-built costs, numerous design and scope changes mean doing so accurately is not feasible. Instead, the key issues affecting costs of the building have been analysed, in the building overall and then in the prefabricated timber systems. A summary of the building costs is presented in Table 8-3 below.

Table 8-3 Actual Cost of STIC Office building

Task	Cost
Reconstruct	$NZD 8,000
Excavation & concrete	$NZD 18,980
Structural work	$NZD 88,072
PSP wall system & exterior cladding	$NZD 66,357
Interior linings & floor coverings	$NZD 16,022
Mechanical heat & vent	$NZD 7,100
Plumbing & drainage	$NZD 7,707
Electrical	$NZD 13,697
Exterior ramp & balustrade	$NZD 9,525

Fire	$NZD 4,837
Overheads	$NZD 26,986
Variations	$NZD 4,099
Macalloy system (Post-tensioning)	$NZD 19,318
TOTAL	$NZD 290,700

It can be seen from Figure 8.10 that close to a third of the total costs came from the structural work including LVL structure, structural steelwork and carpentry work (ground floor). This structural package is worth roughly 33% of total costs.

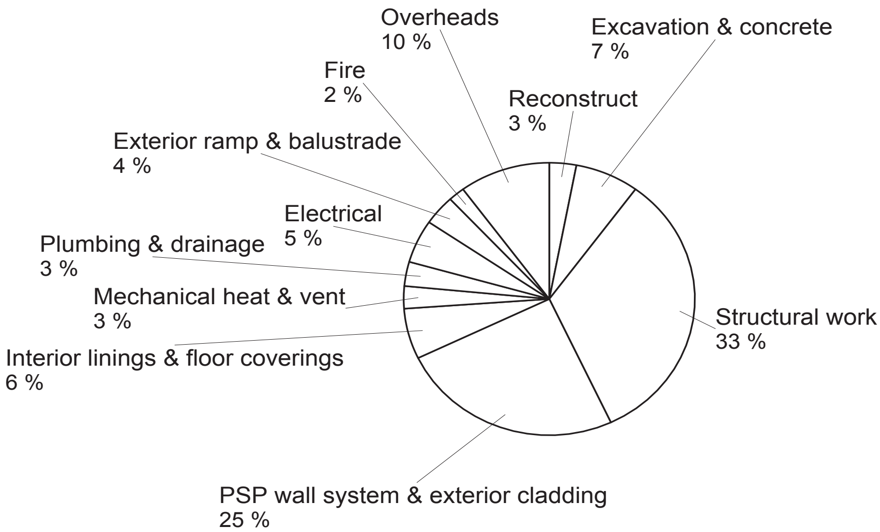

Figure 8.10 Breakup of STIC Office as a percentage of total costs

Source: Smith, Holmes & Carradine (2012)

Due to the scale of this project few Preliminaries and Sundries (P&S) were allowed for, or in fact needed. On a larger project these costs would be something that would need to be accounted for and would lead to higher costs. There is potential for the P&S to be less than traditional forms of construction if the structure could be installed quicker. As mentioned earlier the structural components (frames, walls and floors) for the STIC office were all sourced from the deconstructed experimental test structure at the University of Canterbury. Having all the structural components fabricated and ready to install meant there were no issues ensuring materials arrive on-site in time to allow an optimal erection schedule. This in turn meant there were savings in erection costs as limited time was spent waiting for components to arrive to site, though these potential savings may have been negated due to the extra time taken learning how to install the balloon frames for the first time.

A concrete building of this scale in Christchurch, New Zealand would cost approximately $NZD 1,300 per m^2 (*Rawlinsons New Zealand Construction Handbook* 2009). This is cheaper than the timber option (approximately $2,200 per m^2), though it is important to highlight that precast concrete is a well-established form of construction in New Zealand. Being a pilot project the timber frame, although more expensive at the outset, given time has potential to be cost competitive with the concrete option. With an increase in demand there are potential cost savings in the LVL manufacturing, fabrication process and also installation costs, and as the post-tensioned option becomes more widely adopted the cost gap between the different systems will likely become narrower.

- Cost of prefabricated timber systems

Cost tracking through the prefabrication of the members enabled the calculation and cost of each element. The total cost of the elements delivered on site was $NZD 55,000 excluding transportation.

Table 8-4 Cost Breakdown of elements in STIC Test building ($NZD)

	Materials	Labour	Total	Number in Building	Total from Materials	Total from Labour	Total
Column	810.29	266.00	1076.29	6	4861.76	1595.98	6457.74
Beam	777.03	226.00	1003.03	8	6216.24	1808.00	8024.24
Wall	578.44	303.74	882.18	4	2313.76	1214.96	3528.72
Floor unit	652.88	520.88	1173.75	11	7181.68	5729.68	12911.36
Gravity Beam	814.19	337.50	1151.69	1	814.19	337.50	1151.69
Edge Beam	567.16	450.00	1017.16	4	2268.64	1800.00	4068.64
Steel BC	586.14	337.50	923.64	6	3516.84	2025.00	5541.84
Timber BC	48.44	52.50	100.94	6	290.64	315.00	605.64
Dissipater B-C	253.80	30.94	284.74	32	8121.60	990.08	9111.68
Dissipater C-F	215.68	8.25	223.93	12	2588.16	99.00	2687.16
U-Shaped Plates	160.37	35.60	195.97	8	1282.96	284.80	1567.76
					39456.47	16200.00	55656.47

Source: Smith, Holmes & Carradine (2012)

*Refers to each double T unit floor unit

Note:
BC = beam/column connection
CF = column/floor connection
No. = Number – quantities of elements
UFP = U-shaped flexural plate

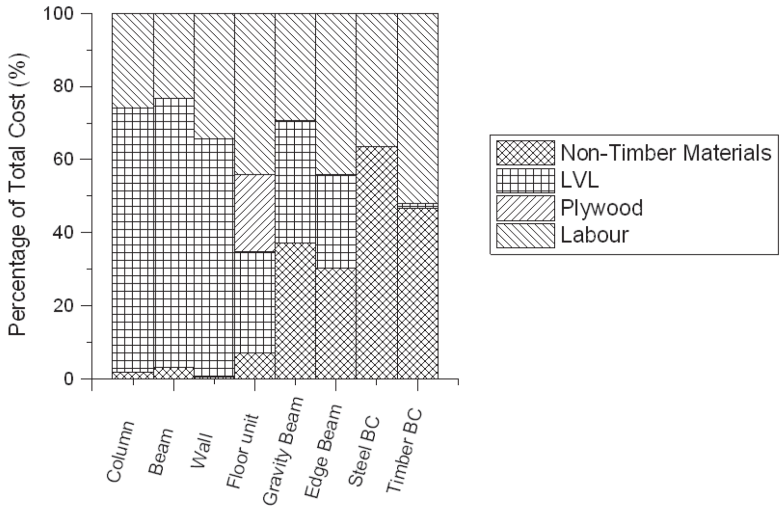

Figure 8.11 Percentages of Labour and Material Costs for STIC Test Building
Source: Smith, Holmes & Carradine (2012)

The frame structure, walls (including edge beams) and floors (including gravity beam) came to a total of $NZD 37,800. $NZD 17,700 (47%) of this was engineered timber. Most of this timber was LVL, however $NZD 2,700 (43% of the timber cost for the floors) was the cost of the non-structural plywood. On average the LVL makes up 70% of the total cost of the lateral resisting system with most of the remaining cost being labour (28%). The floor units showed a labour cost of $NZD 7,200 (44%) indicating a higher level of fabrication was required than the lateral elements. This high labour cost supports the data from case study 1, where labour constitutes a significant amount of overall cost of floor systems.

Figure 8.11 above highlights that for columns and beams elements, LVL material components make up close to 80% of overall costs. And on average across all elements, LVL components make up 70% of total costs and labour 28%. This is an interesting finding and is important when relating back to Porter's five forces analysis performed in Chapter 7 - where it was established that manufacturers have a power situation over fabricators in the supply chain. The market is an oligopoly with only a few dominant suppliers. This data highlighting the LVL making up a large overall percentage of costs is important to support the supply chain model in chapter 7. From this it is important that manufacturers play more of key role in the supply chain of prefabricated timber systems, as they have the power to influence the overall costs delivered to the end customers.

This increased labour cost also occurs for the edge beams and to a lesser extent the gravity beam indicating that it is directly related to the notched connections present in all of these elements. Two types of beam to column joint were implemented in the frame. Table 8-4 shows a clear difference in the cost of the two methods with the steel joints costing $NZD 900 each, 9 times more than the timber joints at $NZD 100 each. This cost disparity comes from a combination of the increased prefabrication time and the increased cost of materials (steel BC materials cost 12 times more than the timber BC). It is common in practice that a Quantity Surveyor will refer to a buildings cost as a per m^3 value for beams, columns and walls and m^2 values for flooring. The choice of beam to column joint on the overall construction cost is clear with the cost per m^3 doubling when a steel beam column joint is used. The timber beam to column joint connection showed a similar test performance (Newcombe, Pampanin & Buchanan 2010a). Due to the large number required the steel dissipation devices also add a significant cost ($\approx$ 2,000 $NZD/$m^3$). Adding a steel beam to column joint and dissipation devices to the frame triples its overall cost. This is similar for the walls system.

QUALITY ISSUES

Feedback from Construction Manager 1 on the project outlined that surprisingly the LVL performed well whilst left out in the open conditions. The LVL was left out in the open either fully- or semi-exposed to the elements for around 7 weeks and remained straight. These findings were different to that in case study 1, where the LVL was left out in the elements on the shipping docks and became cupped. If solid sawn timber were to be used, particularly for the façade support beams, significant warping would have ensued. There were also minor quality issues relating to the finishes of the beams and columns. This was attributed to the fabrication process in the supply chain (as outlined earlier) being relatively primitive in nature, so exact mm tolerances were difficult to achieve unless very skilled workshop staff were used.

8.3.3 Case study analysis & theory testing

Similar to case study 1, this case study adopts the same seven steps as a framework to test structural contingency theory and steps 1 to 3. Also similar to case study 1, the analysis of steps 1, 2 and 3 has not been repeated here.

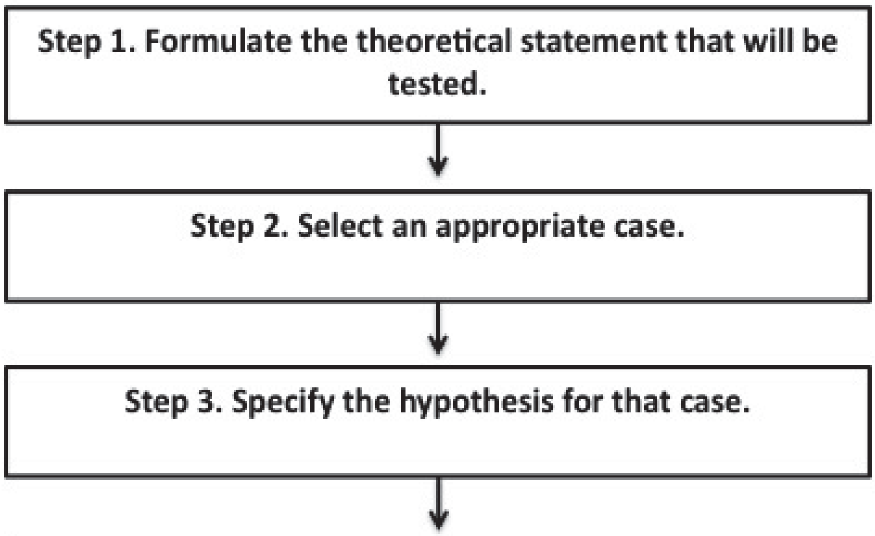

Figure 8.12 Theory testing from case studies

Step 4. Measure the relevant variables.

In the STIC office case study above, data evidence is obtained through an interview and documentation from the project. Measurement entails determining whether X is present and whether Y is present. The result of this measurement is the 'observed pattern'. X is related where there is a lack of integration in the supply chain and where it is not structured in a way that best suits the non-residential environment, and this leads to Y which refers to cost, time and quality issues along the supply chain.

Step 5. Test the hypothesis.

Testing consists of comparing the observed pattern with the expected pattern. The observed pattern from the STIC office case study highlighted that a number of issues along the supply chain in relation to time, cost and quality were caused as a direct result of the structures of organisations along the supply chain. The issues that affected the performance of the prefabricated timber systems in regard to time, cost and quality are discussed in further detail below.

TIME & COST

A number of issues occurred during the installation stage of supply chain which led to extra time. With EXPAN being a innovation and the STIC office being one of the first buildings to use the technology, no organisations have the services or ability to offer specialist installation of these systems. In the end the head contractor undertook the role of installing the systems for the building. Other organisations involved in the production and delivery of ETO products such as steel structural systems and precast concrete generally offer specialist installation services. Moreover, in Europe timber companies generally offer a vertically integrated approach to clients in the non-residential market. As part of this service offering, they generally have a team of specialist installers who help ensure timber systems are installed as efficiently as possible.

The fabrication stage is also a key area of the supply chain that impacts on the time and cost of prefabricated timber systems. As shown in Table 8-4 and Figure 8.10, a number of prefabricated timber items labour makes up a substantial amount of costs. This high labour percentage relates back to fabrication companies being set up as small job shops, with little capital. The size of companies is a key contingency that can affect time and cost, where these fabrication companies are established for small scale production – with Fabricator 1 in this case predominantly being set up as a glulam manufacturer. Having their business structured in this way means they aren't very efficient in the production/fabrication of timber systems. This results in high overheads and limited capacity, which affects both time and cost, particularly on larger non-residential projects.

Figure 8.10 depicts that the cost of LVL material input equals close to 80% for columns and beams. Following on from Porter's five forces analysis in Chapter 7, where it was demonstrated manufacturers have power over fabricators due to their size and market oligopoly. When the supply chain is structured in this way it will always potentially lead to higher LVL input costs as the manufacturers have power to essentially control prices of supply to fabricators. This poses an issue, particularly for non-residential projects, where concrete and steel substitutes provide a cap on prices, if prefabricated timber systems want to be competitive and take away market share. If there was more integration and strategic alliances between Fabricator 1 and Manufacturer 1 there is potential to develop more cost effective systems. This change in the structure of the supply chain would help facilitate entry into the non-residential market through structuring the supply chain in an integrated manner that better meets the needs and expectations of this environment.

As outlined in section 5.5.4, the expected pattern in this research is, when there is fragmentation along the supply chain and companies are not structured in a way that best suits the non-residential market (which has unique market needs and expectations - section 7.3), it that time, cost and quality issues will occur as a result. The observed patterns from this case study supported and matched this expected pattern, where all the installation issues affecting time where caused as a result of lack of skills in the company involved in the installation of timber systems. In Europe the majority of ETO timber companies offer specialist installation services, which helps minimise and alleviate these time delays. Similar to case study 1, even though Fabricator 1 has skills and expertise to deliver products to the non-residential market, it lacks the size and scale to cost and time to efficiently deliver structural systems competitively.

Step 6. Formulate the test result.

'The test result is either a *disconfirmation* of the hypothesis or a *confirmation*' (Hak and Dul 2009b p. 8). From the data collected in this case study through both *interview* and *documentation,* which was analysed in step 5 above, the hypothesis is confirmed that when condition X is present (the supply chain isn't structured in a way that best meets the needs and expectations of the environment i.e. lack of integration and communication) outcome Y is present. Where outcome Y relates to time, cost and quality issues occurring as a result of condition X, organizational structures that don't suit the environment and lack of integration along the supply chain result in a number of performance issues (time, cost and quality) for prefabricated timber systems.

Step 7. Formulate the implications of the test result for the theory.

'Conclusions about the robustness of a theoretical statement cannot be drawn on the basis of just one test, but only after a series of tests. Hence, discussing the implications of a test result always implies comparing the result with those of earlier tests in a series of replications' (Hak and Dul 2009 p. 8). Through the confirmation of the hypothesis in this case study it supports the findings in case study 1. The following case studies will help provide another series of tests to further confirm or disconfirm the hypothesis in relation to the supply chain of prefabricated timber systems.

8.3.4 Conclusion

The STIC test building case study highlighted a number of time, cost and quality issues that occur along the supply chain. It was confirmed that these observed issues occurred due to a number of factors, including lack of communication and collaboration amongst supply chain members, and companies along the supply chain not being structured in a way that best meets the market needs and expectations of the non-residential market. Through the use of the seven-step framework, structural contingency theory was tested and confirmed for this particular case study - as the expected patterns and observed patterns matched.

8.4 Case study 3 - Nelson Marlborough Institute of Technology (NMIT) Arts & Media Centre Nelson, NZ

8.4.1 Introduction

Following on from case study, the STIC office project, this section intends to establish further key issues that affect the time, cost and quality along the supply chain on another project using prefabricated timber systems. In particular it looks into how the organisations along the supply chain impact on the performance of prefabricated timber systems. The building used in this case study is the Nelson Marlborough Institute of Technology (NMIT) Arts & Media Centre at Nelson, NZ. It was the first approved build-in-wood demonstration building under a New Zealand Government initiative. The project was initiated in 2008, through discussions with the NZ Ministry of Agriculture and Forestry (MAF) and NMIT staff.

MAF are looking into how climate change can be mitigated by the forestry industry – in particular how the planting of more trees can create carbon sinks and sequester carbon dioxide from the atmosphere. Well-managed forestry plantations not only sequester carbon from the atmosphere but can also help improve water quality and prevent erosion. MAF contributed $1 million towards design fees for the NMIT project and supported a design competition for the project. Construction commenced towards the end of 2009 and the building officially opened in March 2011.

Data collected from this case study includes *documentation, interviews* and *direct observation.* Interviews were conducted with a number of key project members; details of these interviewees are outlined in Table 8-5.

Table 8-5 Interviewee details from NMIT project

Interviewee	Company Type	Country	Work Experience
Architect 1	Architecture	NZ	15 - 20 years
Construction Manager 1	Head Contractor	NZ	20 + years
Floor Manufacturer 1	Manufacturing	NZ	15 - 20 years
Plant Manager 1	Manufacturing	NZ	20 + years
Project Manager 1	Head Contractor	NZ	20 + years
Senior Technical Advisor 1	Fabrication	NZ	20 + years

A total of six interviews were conducted for this case study. All of these were conducted during the construction phase of the project. Whilst undertaking these interviews, site visits were also made to the project site and fabrication and manufacturing facilities - *direct observations* of any issues were made during these visits. *Documentation* from the project was also obtained, including cost plans, drawings and construction programs. For this particular project a lot of information on the project was available through a MAF report (John et al. 2011). So the following analysis of issues is a combination of primary data from interviews and observations as well as secondary data from the MAF report (John et al. 2011).

Manufacturer 1 is an LVL manufacturer based in Nelson, NZ. They have a capacity to produce 300m^3 of LVL billets per day. Materials are moved throughout the plant with large forklifts and overhead gantry cranes and they tend to store materials in inventory for substantial periods of time (up to 45 days). LVL billet is manufactured in three standard depths 36mm, 45mm and 63mm, and are typically manufactured at widths of 1200mm. There is also a continuous cold press system, which has the capability to press up to 12m^3 at any one time. There is potential to use this cold press system to bond multiple billets to make deeper units. Fabricator 1 is also based in Nelson, NZ and specialises in manufacturing glulam. They have 8 – 10 staff members and the manufacturing process consists primarily of manual labour, with very little automation and a high degree of materials handling required. The presses and machinery used to manufacture glulam can also be used to fabricate (relaminate) LVL billets. Different cross sections can be manufactured and relaminated up to 33m in length.

Figure 8.13 NMIT project – prefabricated timber structural system installation

Figure 8.13 shows the project during the construction phase and a number of the different prefabricated timber structural systems used on the building including columns, beams and shear walls. LVL billet was used to form a number of differently sized prefabricated timber systems. Columns were 400 x 300mm and 400 x 400mm in size and were each three stories in height. Primary beams consisted of double LVL beams that spanned 9600mm. Shear walls were used for bracing in the longitudinal direction and were 3000mm wide. In addition, Potius timber floors systems were prefabricated and, once they were installed on-site, a 75mm concrete topping was applied. The floors were flange hung on the LVL primary beams to help minimise the overall depth at floor to primary beam junction. Floor units were 6000 x 1200 x 300mm in size.

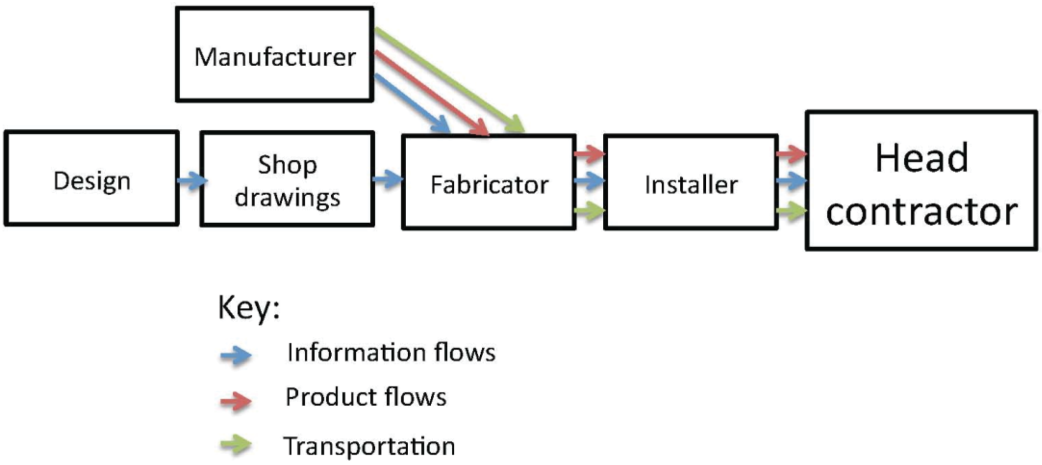

Figure 8.14 Supply chain for prefabricated timber elements on NMIT

8.4.2 Key issues affecting performance (time, cost and quality)

The key issues affecting time, cost and quality along the supply chain of this case study are detailed below. As outlined earlier these issues were established from primary data from *interviews* with project team members as shown in Table 8-5 and *direct observations* from site visits. Secondary data including d*ocumentation* and information was sourced from the MAF report John et al. 2011.

TIME ISSUES

A number of issues along the supply chain affected the time of the prefabricated timber systems on the building. Table 8-6 below outlines the key issues that impacted on the building schedule. Overall the structural work took 123 days instead of 100 – approximately 25% longer than predicted. The following section will look into these key issues that affected time and in particular how the organisations along the supply chain relate to or create these issues.

Table 8-6 Time for key prefabricated timber structural systems on the NMIT project

Building schedule*	**Planned building schedule (days)**	**Actual building schedule (days)**
Shop drawings	33	55
Approval of shop drawings	10	10
Fabrication of columns, beams and shear walls	30	47
Fabrication of floor systems	30	21
Delivery of columns and beams	3	26
Delivery of floor systems	3	28
Erect columns and beams	17	25
Erect shear walls	10	10
Erect flooring	6	20
Total time for structural elements^	100*	123*

Source: John et al. 2011

* It is inappropriate to simply add all activities to give overall time, as some activities are sequential and some are concurrent.

^ Structural elements refer to prefabricated timber systems

- Shop drawings had to be redrawn for the fabrication workshop

  <u>Took 55 days instead of 33 days → 67% longer than planned</u>

Lack of communication between architects and engineers meant shop drawings for fabrication had to be completely redrawn, reviewed and then re-submitted - as opposed to developing the original drawings produced by architects and engineers. Time savings could be achieved through full integration of drawings between all parties. This could be facilitated by increased communication between parties as well as establishing who takes responsibility for the fabrication of drawings. Senior Technical Advisor 1 from Fabricator 1 outlined the 'fabricator doesn't have capacity or expertise to produce shop drawing for larger projects'. To prevent the double up of work, increased communication and integration is important, particularly between the structural engineer and the fabricator, and will help reduce fabrication errors and also produce designs that are more cost and time efficient to produce.

- Fabrication of LVL columns & beams
  Took 47 days instead of 30 days → 57% longer than planned

Fabricator 1 is a Nelson based company, which specialises in manufacturing glulam and has approximately 10 staff. Their fabrication process is primarily driven by manual labour and is set out in a manner which requires a large amount of material handling. Fabricator 1 typically uses the same presses for manufacturing glulam to fabricate LVL members. The presses are capable of fabricating a number of different cross sections up to 30m in length and with varying cross sections. These are generally limited to single glue lines at a time, so lead times on beams and other units are quite long.

Long lead times that are required due to the slow fabrication process can be allowed for in the construction program. The major issue is more in relation to the fact that once these lead times have been allowed for in the program it is critical that elements are fabricated in time and can be delivered to site as per the construction program. Construction Manager 1 outlined that they had a number of issues in regard to obtaining elements on time and this led to delays on the project. Construction Manager 1 seemed to have a degree of animosity towards Fabricator 1, as he believed that not enough front-end work was done on the project, and that they could have pre-made a number of the elements before the shop drawings were finalised. Senior Technical Advisor 1 from Fabricator 1 argued that not enough time was allowed for in the program and that they should have been engaged earlier in the procurement process to allow them to do more front-end work.

The point is not about establishing who is right or wrong in the above situation but more so pointing out there is a larger issue present. Until the fabrication process becomes more efficient the entire procurement process for prefabricated timber systems on larger multi-storey non-residential building needs to be addressed. Fabricators will need to be involved from the concept stage (dependent on the size of project and how much fabrication needs to occur) and, during pre-tender, a schedule of rates should be established with a fabricator to allow them to start to order materials and do the front-end work. Fabricator 1 revealed the timing of stages during the supply chain for a project the same size as NMIT, approximately 400m^3 of LVL (excluding raw material extraction), were:

- 6 weeks for LVL lead time/supply
- 4 weeks for shop drawings to be developed
- 10 weeks of work to fabricate all the LVL structural elements for the building.

These figures listed above are questionable as it was outlined by Manufacturer 1 that the actual LVL components required for the NMIT building would only take approximately one and a half days to manufacture. To put this into some perspective, it took less than half a working week to manufacture LVL for the project and approximately 10 weeks to fabricate elements. Manufacturer 1 is an LVL and Medium Density Fiberboard (MDF) manufacturer based in Nelson, NZ and was responsible for supplying LVL for the project. The plant in Nelson has the capacity to produce 300 m^3 of LVL per day and can produce standard LVL sections in three different depths, 36mm, 45mm and 63 mm. Standard billet widths produced are 1220 and 610mm. The length of LVL billets is primarily governed by transportation limits and can range from 12 – 18m. Manufacturer 1 also has a continuous cold press system, which was not unused, though it has a capacity to press 12m^3 at any one time. In the future this may be utilised for the bonding of multiple billets to make up deeper units. On this project there weren’t too many issues in regard to transportation of material to the fabricator as Fabricator 1 was located only a few kilometres down the road.

When taking these lead times into consideration, it is a fair assumption that a traditional lump sum procurement method (where a design is completed 100% and then put out to tender) won't be the most ideal method for a large timber building. Depending on the amount of excavation required, the lead time required to fabricate the timber systems would make it potentially unfeasible and there would be huge risks associated with the delivery of timber elements to site on time.

- Delivery of prefabricated timber systems from fabricator 1 to site
  <u>Took 26 days instead of 3 days → 866% longer than planned</u>

Due to slow fabrication times, just-in-time erection on site could not be optimised. Prefabricated timber systems were delivered by truck and were ideally placed directly into position straight from the truck. However, as fabrication of elements was slower than expected, some elements had to be stored on-site as they were awaiting arrival of other elements before they could be installed. Ensuring components were stacked on trucks in a manner which facilitated direct installation was also important. This requires direct communication between the fabricator and the head contractor. Adequate storage in the fabrication workshop is also important, because if the fabricator don't have the capacity to fabricate elements just in time, they will have to fabricate and store items prior to the construction phase so the delivery and installation of elements to site can be optimised. This presents potential inventory problems for fabricators – particularly those that don't have the space to store items. Going forward, particularly for larger projects i.e. above 500m^3, the organisation of the fabrication process and delivery of items to sites presents a large opportunity to achieve huge time and cost savings.

- Erection of prefabricated timber systems
  <u>(Took 25 days instead of 17 → 47% longer than planned)</u>

Following on from the above, due to the spread of deliveries, construction sequence and cranes were not fully utilised – the installation of members took close to 50% longer than planned. Prefabricated timber systems being lightweight have the potential to save time during installation. Crane size and location on-site is also an important consideration when achieving time savings. If a larger crane is used that can install all elements on the project from the one position time savings that can occur as only one materials delivery and handling point will be needed. Alternatively a number of smaller cranes could be used and materials could be installed from a number of different points.

COST ISSUES

- Labour intensive fabrication process

The key issue in the fabrication process is that it is extremely labour intensive with little to no automation. Construction Manager 1 on the NMIT project remarked that 'the process at fabricator 1 hasn't changed since I was undertaking my carpentry apprenticeship some 20 or so years ago.' Typically LVL is supplied in billets by a manufacturer, and once they arrive at the fabrication workshop are cut by hand with a large circular saw into desired widths. Adhesive is then smeared and they are put into the press where pressure is applied to laminate the members together. The beams are then sanded by hand with a belt sander before they are delivered to site. Architect 1 explained that specifications play a large part in costs, particularly specifications to the required finish levels. Leaving LVL exposed can lead to 'huge labour costs, cutting and sanding all LVL billets.' The shear walls on the NMIT project alone took a worker 16hrs to sand and finish to a quality acceptable for the project. If this person is being charged out at $60 per hour it roughly equates to $2000 in labour costs alone just to sand each shear wall.

- Cost estimate doesn't include design fees, which were subsidised by $1 million prize money provided by MAF

Innovative construction systems typically take longer to design, due to the designers' lack of familiarity and experience. There is limited cost data available on the costing of design fees for the project. Presently very few design consultants are experienced in the design of large multi-storey non-residential buildings. In particular structural engineering is one area of concern and is reiterated in the bullet point below. Going forward, as design companies' structure themselves in a way that they become experienced and skilled in the design of multi-storey non-residential buildings, the cost of design fees will reduce and become comparative with steel and concrete design.

Construction Manager 1 outlined approximately $80,000 could have been saved over specifications by structural engineers. Engineers from the University of Canterbury, Christchurch highlighted a number of items weren't needed i.e. steel shoes for shear walls and oversizing of some elements. However, the engineer on the project insisted – at the end of the day they had to sign off on the project! Nevertheless, this highlights the potential benefits of collaboration between universities and engineers for these pilot buildings and the potential savings that could be achieved. The aforementioned supports the notion that there is lack of structural design expertise, not only on this project, but in the Australian and NZ industry as a whole.

QUALITY ISSUES

- LVL laminations used in columns are starting to peel open so small gaps are present.

Not long after the project completion date small gaps began to appear between the LVL laminations in the columns. This issue can be traced back to the fabrication process and quality control, in particular insufficient pressing of laminations in the columns. As mentioned earlier, Fabricator 1 on this project is primarily a glulam manufacturer, though had of late begun to undertake fabrication work re-laminating LVL. Fabricator 1 has structured its business to manufacture glulam though, when certain projects arise, transfer across into fabrication work. Issues then potentially arise when Fabricator 1 uses the same equipment to manufacture glulam as it does to re-laminate LVL members and it is imperative that quality control is maintained. Otherwise issues with glue lines during re-lamination will continue to occur.

- QA during fabrication and surface treatment of LVL members

Fabricator 1 also has timber treatment facilities on site with a Light Organic Solvent Preservative (LOSP) tank that is the longest in NZ and can treat dimensions of roughly 15800 x 1200 x 1200. Finished goods are typically stored for no more than one week, though some space is available to store materials. Fabricator 1 also has its own kiln with which they dry and cut their own timber for glulam purposes.

8.4.3 Case study analysis & theory testing

Similar to case study 1, this case study adopts the same seven steps as a framework to test structural contingency theory and steps 1 to 3. Also similar to the analysis in case study 1, steps 1, 2 and 3 have not been repeated here.

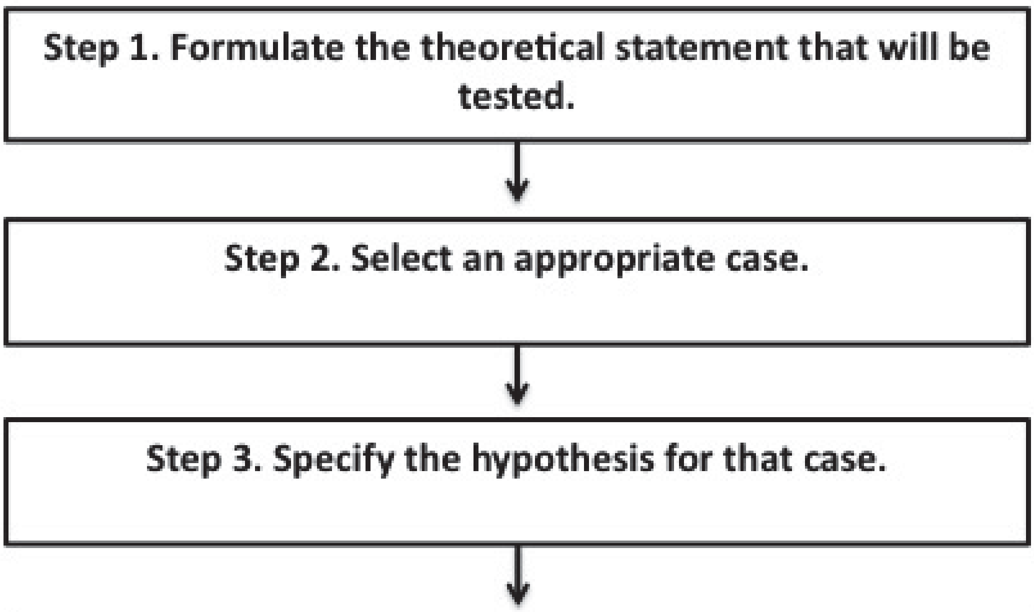

Figure 8.15 Theory testing from case studies

Step 4. Measure the relevant variables.

In the NMIT case study above data evidence is obtained through *interviews*, *documentation* and *personal observations*. Measurement entails determining whether X is present and whether Y is present. X is satisfied where there is fragmentation and a lack of integration in the supply chain and where supply chain is not structured in a way that best suits the non-residential environment. Y refers to cost, time and quality issues along the supply chain. The result of this measurement is the observed pattern.

Step 5. Test the hypothesis.

Testing consists of comparing the observed pattern with the expected pattern. As highlighted in the above section 8.4.2 a number of issues occurred in relation to time, cost and quality. The observed pattern from these issues is that a lot of them were caused due to the supply chain and organisations along it not being structured to suit the non-residential environment. Manufacturer 1 has their operations set up to suit the residential market, where they supply a commodity product with little integration in the supply chain downstream, though the data highlighted that Fabricator 1 has the biggest influence on time, cost and quality. Fabricator 1, similar to other fabricators in NZ and also Australia, is an organisation structured to predominantly service the residential construction market as well as the glulam market. They are structured to manufacture glulam in the traditional manner with 'lock and bolt' presses and very little automation.

This fabrication model lends itself to smaller niche projects typically in the residential market. Fabricator 1 has very limited undercover storage, which presents itself as an issue on larger projects like NMIT that require long lead times. Members should be fabricated prior to when they are required on-site and then stored in the fabricator yard, undercover, so they can then be delivered to site in a just-in-time manner. Moreover, Fabricator 1, typically working on smaller projects, has limited integration with the designer (structural) or manufacturer (LVL) as being a glulam manufacturer it typically acts as a material supplier. So they have little experience or capability with the production of shop drawings. This in conjunction with lack of collaboration between the structural engineer and the architect helped the substantial time issues that resulted from reproducing shop drawings. The prefabricated timber systems used on NMIT are ETO products though the data has clearly highlighted that Fabricator 1 is set up as a MTO company and Manufacturer 1 is predominately an ATO company. (Refer Table 3-2 for further details on the differences between ETO, MTO and ATO.)

Designers are typically experienced in design steel and concrete building design, and have limited expertise in timber design in larger multi-storey construction.

This leads to time and cost issues, as it takes longer and is in turn more costly for them to design. Following on from above, a lack of integration between design consultants (architects and engineers) caused significant time delays in the production of the shop drawings used during the fabrication process on the project.

Step 6. Formulate the test result.

'The test result is either a *disconfirmation* of the hypothesis or a *confirmation*' (Hak and Dul 2009 p. 8). This case study has confirmed the hypothesis by highlighting that outcome Y is present. Outcome Y is that, when the organisations and the supply chain aren't structured in a way that meets the needs and expectations of the non-residential environment, issues will occur in relation to time, cost and quality of prefabricated timber systems. These issues are seen as the observed pattern and are outlined in step 5. This observed pattern matches the predicted pattern so the hypothesis is confirmed.

Step 7. Formulate the implications of the test result for the theory.

'Conclusions about the robustness of a theoretical statement cannot be drawn on the basis of just one test, but only after a series of tests. Hence, discussing the implications of a test result always implies comparing the result with those of earlier tests in a series of replications' (Hak and Dul 2009 p. 8). The confirmation of the hypothesis in this case study supports the findings in case study 1 and 2, which also confirmed the hypothesis (outlined in step 3). The following case studies will help provide another series of tests to further confirm or disconfirm the hypothesis in relation to the supply chain of prefabricated timber systems.

8.4.4 Conclusion

The NMIT building case study highlighted a number of time, cost and quality issues that occur along the supply chain for prefabricated timber systems. The results from this case study were similar to those on case study 1 and case study 2 where the observed issues occurred for a number of reasons. These were primarily due to lack of communication and collaboration amongst supply chain members, and companies along the supply chain not being structured in a way that best meets the market needs and expectations of the non-residential market. Through the use of the seven-step framework, structural contingency theory was tested and confirmed for this particular case study - as the expected patterns and observed patterns matched.

8.5 Conclusion

This chapter presented the findings from three building case studies – two in NZ and one in Australia. The three building case studies were used to test structural contingency theory in relation to the supply chain of prefabricated timber systems. Through the use of the seven-step framework and the pattern matching technique, structural contingency theory was tested and all three building case studies confirmed the hypothesis as the expected patterns and observed patterns matched in all cases.

From the data and analysis in this chapter the case studies can be classified as the following. Case study 1 – UTS floor systems is as a 'worst case scenario' and then case study 2 – STIC Office as a 'bespoke installation' and then finally case study 3 NMIT as a 'government sponsored prototype or showcase building'. Each of these case studies has relevance in highlighting supply chain effectiveness and structure, though are not typical construction projects, so there are limitations in whether the issues conceived would be the similar or different on typical projects. Also given the EXPAN technology is in its infancy and they were the only construction projects available at the time of research they still have strong value and lessons learned for future projects. As more projects are built using the technology the supply chain issues and subsequent model(s) can be further refined and validated.

The three case studies also highlighted a number of time, cost and quality issues that occur along the supply chain for prefabricated timber systems. Similar to the findings from interview cases studies, issues highlighted were along similar themes including lack of communication and collaboration amongst supply chain members, lack of fabrication capacity, and lack of design expertise. One key issue that was touched on in the interview case studies, though really made clear in the building case studies, was that companies along the supply chain were not structured in a way that best meets the market needs and expectations of the non-residential market.

Chapter 9 Model validation

9.1 Introduction

The building case studies in Chapter 8 established that structural contingency theory was supported in relation to prefabricated timber systems. This section outlines how the SBE model developed in Chapter 7 can be used to improve the performance (time, cost and quality) along the supply chain for prefabricated timber structural systems. As outlined in Chapter 7 the SBE model was developed from the issues established in case study interviews, highlighted in Table 6-2 and supported with strategic procurement literature and structural contingency theory. The first part of this section undertakes a cross case analysis between the issues along the supply chain in the part one case study interviews and part two building case studies. Next to be examined is how the SBE model is modified to incorporate findings from building cases and then how, when it is adopted, it can help improve the performance (time, cost and quality) of prefabricated timber systems.

9.2 How the SBE model can improve time, cost and quality along the supply chain of prefabricated timber systems

9.2.1 Cross case analysis of key supply chain issues in part one case studies (interviews) and part two case studies (prefabricated timber systems in buildings) in Australia/NZ

The interviews in Chapter 6 highlighted a number of key issues along the supply chain that impact the time, cost and quality of prefabricated timber systems. Table 9-1 below summarises the key issues established from the interviews and building case studies. A level of importance ranking is attributed to each of the issues listed. This is expressed as a percentage, and for the part one case study interviews this percentage was determined by nodes established in the NVivo 9 report; the issues with the highest number of nodes were ranked and given a percentage based on this ranking. The percentages in the part two building case studies were created by aggregating data across the three building case studies including *documentation, interviews* and *personal observations.* The key issues from the data across the project case studies that occurred most frequently were given the higher level of importance rankings.

Table 9-1 Cross-case analysis of issues in part one and part two case studies

Issues	**Level of importance ranking (%)**	
	Part one - Case study (Interviews)	Part two - Case study (Buildings)
Fabrication process	40%	50%
Fragmentation between supply chain	25%	20%
Building code requirements	12.5%	n/a
Design and detailing	10%	10%
Installation capacity	7.5%	10%
Logistics/ transportation between stages	5%	10%

The issues highlighted in the part one case study interviews focused on general issues across the prefabricated timber system industry. The three building case studies focused on highlighting issues on individual projects, with the aim of discovering further issues that weren't highlighted in the case study interviews. The building case studies were also undertaken to establish how the organisations along the supply chain contribute to create these time, cost and quality problems. The results from the building case studies supported the issues highlighted in Chapter 6 and, through detailed analysis of documentation, personal observations and interviews with key stakeholders obtained on the projects, more issues and their causes were able to be uncovered.

As shown in Table 9-1 the key issues along the supply chain to affect time, cost and quality of prefabricated timber systems were almost identical in both part one and two of this research. One key thing that changed between the two parts was the level of importance ranking of these issues. In the building case studies the fabrication process came out as the highest-ranking issue at 50%. This issue around the fabrication stage topped the level of importance ranking in both part one and part two of this research. Across the three building case studies data obtained from documentation, interviews and personal observations highlighted that approximately half of the time, cost and quality issues were attributable to the fabrication process. Time and cost in particular were key areas that were directly affected by the fabrication process.

The building case studies as discussed earlier provided more details on how the fabrication companies affect the time and cost of the delivery of prefabricated timber systems. It was established in that discussion that throughout Australia and NZ only a handful of companies are currently able to undertake fabrication work for EXPAN and similar prefabricated timber systems to be used in multi-storey non-residential construction. The majority of these companies are glulam manufacturers who have the ability to undertake fabrication work – though their core businesses are manufacturing glulam. These companies are also focused on the residential market and supplying bespoke components for single storey architectural non-residential buildings.

Fragmentation along the supply chain ranked similarly in both parts of the research – though in the building case studies it ranked slightly lower than in the case study interviews. The case study interviews highlighted that fragmentation between organisations along the supply chain was a key issue and the building case studies supported this. All three building case studies were able to demonstrate fragmentation occurring on real life projects, and highlight that the fragmentation was most prominent between manufacturers and fabricators. They also highlighted that manufacturers have little to no involvement with product once it leaves their plants. It was also established that there is fragmentation between designers, fabricators and manufacturers. With prefabricated timber systems being an ETO product and the decoupling point at the design stage, it is important that designers, particularly architects and structural engineers, are aware of manufacturers' and fabricators' ability and current capacity. Increased levels of communication between structural engineers and fabricators in future can help create cost efficient designs. If the structural engineer is aware of what component dimensions can be fabricated efficiently, they will have a greater ability to design components which can be fabricated more cost and time efficiently, leading to significant potential time and cost benefits. The building case studies also highlighted the lack of collaboration between designers and fabricators in relation to the development of shop drawings. Two of the building case studies in particular highlighted that fragmentation between design consultants and the fabricator led to significant time delays in the production of shop drawings.

Building codes were highlighted in case study interviews as being a key issue that effects time and costs for prefabricated timber structural systems in multi-storey non-residential construction. For timber structural components used in buildings above 3 storeys in height in Australia and NZ a performance based alternate solution is required, which adds time and costs to projects. The three building case studies identified that building codes weren't highlighted as a key issue to affect time or cost. The most likely cause of this was because the structural components weren't used in buildings above three storeys in height so an alternate solution wasn't required.

Design and detailing came in at the same level of importance ranking for both part one and part two of the research. As detailed previously with prefabricated timber structural systems, being an ETO product and the decoupling point being located at the design stage, the design and detailing is a critical process in the supply chain. The case study interviews in Australia and NZ highlighted there is a lack of industry wide expertise in the design and detailing of prefabricated timber structural systems in multi-storey non-residential construction. This inherently leads to cost and time overruns if a designer has to learn structural design with timber from first principles or an architect has to spend more time researching correct detailing techniques. The building case studies supported the findings in the case study interviews though also outlined that, in circumstances where the design and detailing is performed by one of few experienced design consultants in Australia and NZ, design and detailing doesn't pose as such an issue. However, experienced timber design consultants are an exception rather than the norm.

Installation capacity similar to design and detailing expertise was examined in the case study interviews as being an industry wide issue that affects the cost, time and quality of prefabricated timber systems. This is most likely attributed to the lack of large timber buildings completed to date in Australia and NZ. As discussed in Section 5.5.1, only seven buildings have so far adopted EXPAN prefabricated timber systems. The two building case studies in NZ highlighted a number of key issues during the installation process, which is why in part two of the research it is ranked slightly higher in the level of importance. As more buildings may be built and experience increases and lessons are learned from past projects, this issue may slowly start to diminish.

Logistics/transportation between stages in the supply chain achieved the lowest level of importance ranking, at 5%, in the case study interviews in part one. Key feedback from these interviews highlighted that prefabricated timber structural systems are inherently difficult to transport, as they normally aren't stacked on gluts. This makes it difficult to load and unload onto trucks, which leads to higher costs and longer time. Moreover, as timber is hydroscopic and expands and contracts when it gets wet and then dries, the quality of billets can be severely affected if the timber is left out and exposed to the weather. This level of importance ranking increased twofold to 10% in the building case studies. This was primarily due to the issues that occurred in the UTS floor system case study, where there were significant delays in the delivery of materials from the manufacturer to the fabricator.

9.2.2 Modifications to the SBE model to incorporate findings from part two building case studies

As discussed the supply chain model in Chapter 7 was developed from a combination of case study interview findings and strategic procurement literature – this model is outlined in Figure 7.4 Building case studies uncovered further details on the issues along the supply chain that impact on the performance of prefabricated timber systems. The fabrication process in the supply chain was further reiterated as being the key issue to affect time, cost and quality. The building case studies discovered that there is potential for manufacturers to also undertake fabrication work - one of the manufacturers already has the necessary capital to undertake fabrication work, though currently doesn't do so. Having the manufacturers undertake fabrication work would be much more efficient and lead to a number of time, cost and quality benefits.

In Europe CLT is produced in a manner where manufacturers undertake both the manufacturing and fabrication processes. The CLT is manufactured into blank panels and then fabrication work is performed through cutting out panels as per project specifications. By undertaking both of these processes under the one-roof, components don't need to go through two different companies along the supply chain. This has potential to help achieve time and cost savings as the extra overheads and profits wouldn't need to occur for two different companies. In addition, extra double handling and associated logistics/transportation costs and time wouldn't occur. This is particularly important when the manufacturer and fabricator are located significant distances apart and not on the same direct route to the project. Quality issues as detailed in case study one – UTS floor systems – can also potentially be mitigated through cutting out this transportation between the manufacturer and fabricator.

Another reason why the manufacturing companies should undertake fabrication work is that the companies predominantly doing this work at present are glulam manufacturers and fabrication of LVL components is not their core business. Even though these glulam manufacturers are capable of doing the work, all three building case studies in part two of the research highlighted they are inefficient in performing this activity. For LVL manufacturers there is an opportunity to vertically integrate downstream in the supply chain to the fabrication space, not only to maximise gross margins but also (as outlined in the building case studies) because they have the company size to invest in the necessary capital to make the process more efficient.

Harrigan (1984) outlines that the key to using vertical integration is for an organisation to recognise which activities they should perform in-house, how these different activities relate to each other, and how much ownership equity should be invested (risked). The conventional analysis for deciding how much equity should be invested relates to the efficiency of markets, where if the cost of transacting through the market is greater than the cost of administrating through a firm then vertical integration is a sound strategy. As detailed in the case studies the transactions costs associated with going through a fabricator are high and there is potential that this could be performed more cheaply and efficiently if done in-house by the manufacturer.

Following on from this analysis the SBE model has been updated as shown in Figure 9.1. The key change to the model is that the subsidiary of the manufacturer – the SBE – now undertakes both the manufacturing and fabrication work. This will allow the prefabricated timber system to leave the SBE's production facilities ready to be installed on-site. The building case studies highlighted that the development of shop drawings and who takes ownership of this process is a key issue that also needs to be addressed. The SBE is best suited to undertake this process in collaboration with the structural engineer, and the closer this relationship is between the structural engineer and the SBE subsidiary the better. Having a direct partnership with the structural engineer not only helps ensure structural designs are able to be cost and time efficiently fabricated. This relates not only to developing designs that are simple and match fabrication capacity – through ensuring elements are designed to factor in dimensions the LVL is manufactured at. This modification to the SBE model is referred to as *Taper Integration,* and it's where firms integrate either forward (upstream) or backward (downstream) but still rely on outside organisations for a proportion of their supplies or distribution. Taper Integration is recognised, as a good compromise between desires to control adjacent businesses and the need to maintain flexibility.

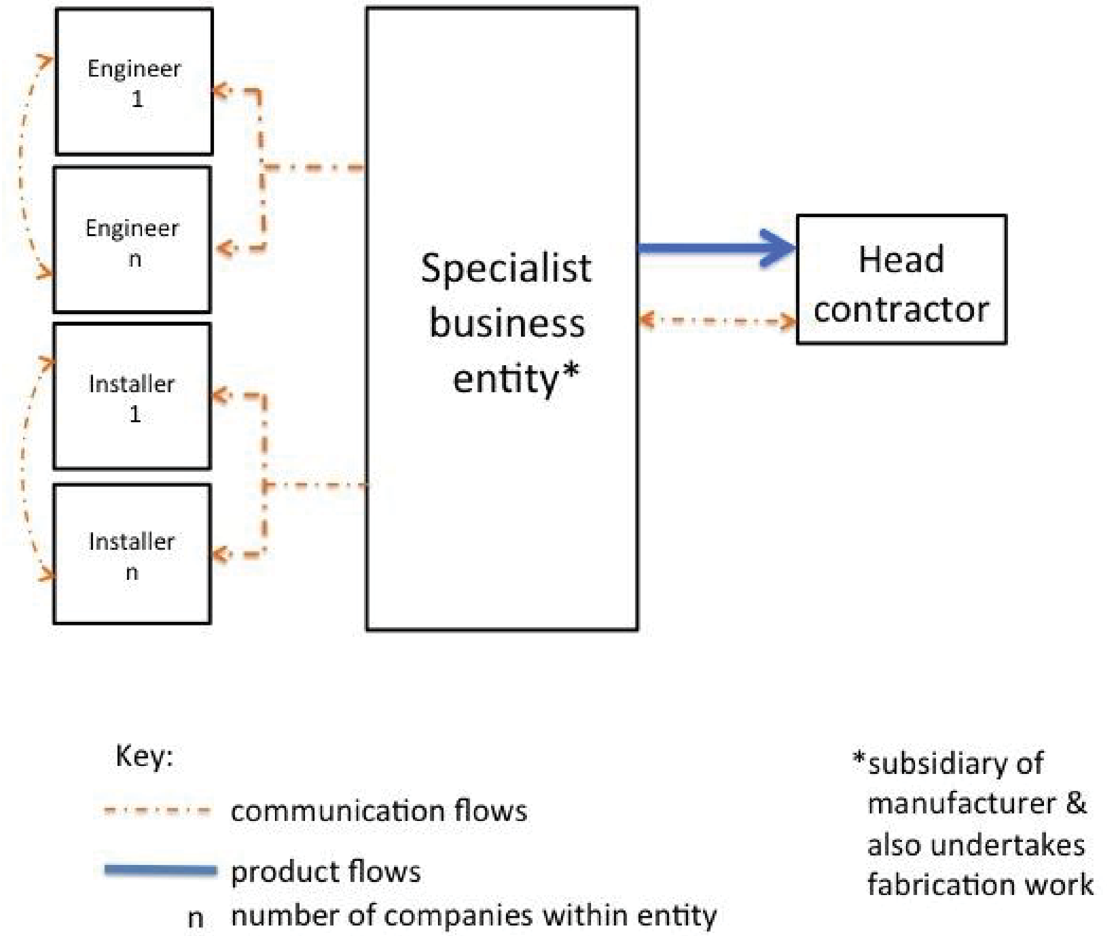

Figure 9.1Updated SBE model

9.2.3 How the SBE model can improve cost, time and quality

The SBE model offers a number of opportunities to improve the time, cost and quality of prefabricated timber systems. This section will use a virtual building case study of a 9-storey commercial office building and compare how the SBE model can improve the performance of prefabricated timber systems compared to the current supply chain. The case study is a redesign for a current concrete building in Sydney, Australia. The building design utilizes the new EXPAN prefabricated timber construction system. This case study will focus on the procurement of the prefabricated timber structural system only – post-tensioning cables are required between the beam/column interfaces though they will not be covered in the supply chain analysis. The post-tensioning systems are not covered because their cost in the overall project costs are minimal, as shown in Table 8-3 from case study 2 STIC office, which showed that the post-tensioning came to 6% of overall costs in comparison to the timber structural work, which equated to 30%. As the macalloy bars used in the post-tensioning system are widely used in concrete construction they already have an established supply chain and don't have the inherent issues associated with the supply chain for prefabricated timber systems in Australia and NZ.

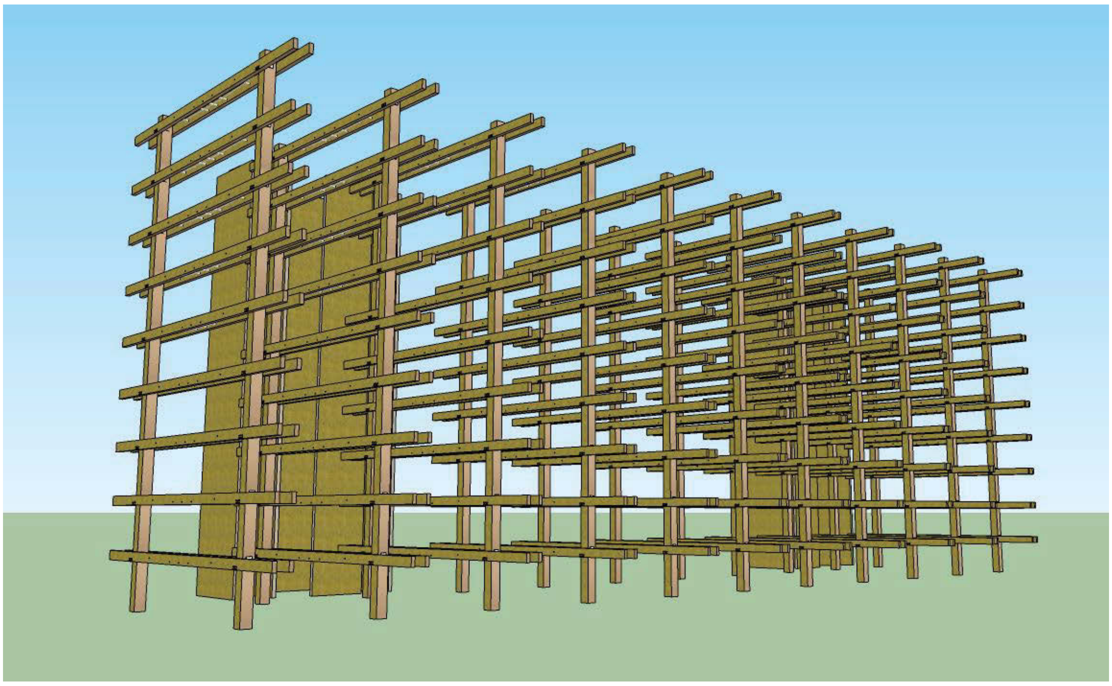

Figure 9.2 Case study building - timber structural system

The timber building is based on a series of gravity only frames and lateral load resisting shear walls. The timber system is to be constructed above two levels of concrete car park that will also include the concrete foundations. HYSPAN LVL or a similar product will be used. Further detail on the structural system and information on connection details are covered in **Appendix F – Virtual building case** study used to test SBE model.

The following section will estimate and compare the costs, time and quality of procuring this prefabricated timber system through the traditional supply chain and then through the SBE. Data used in this analysis is obtained from the building case studies and also IBISWorld industry reports. Data from IBISWorld industry reports were used to obtain cost break-ups of manufacturing and fabrication costs, as manufacturers were reluctant to provide detailing costing's. Figure 9.3 below highlights the different supply chains to the project site, comparing the traditional supply chain to the SBE model. It clearly highlights that, when the manufacturer undertakes the fabrication process, there is a more direct route to the project as under the SBE model the fabricator is now taken out of the supply chain. This can lead to significant time and cost savings, which are outlined below.

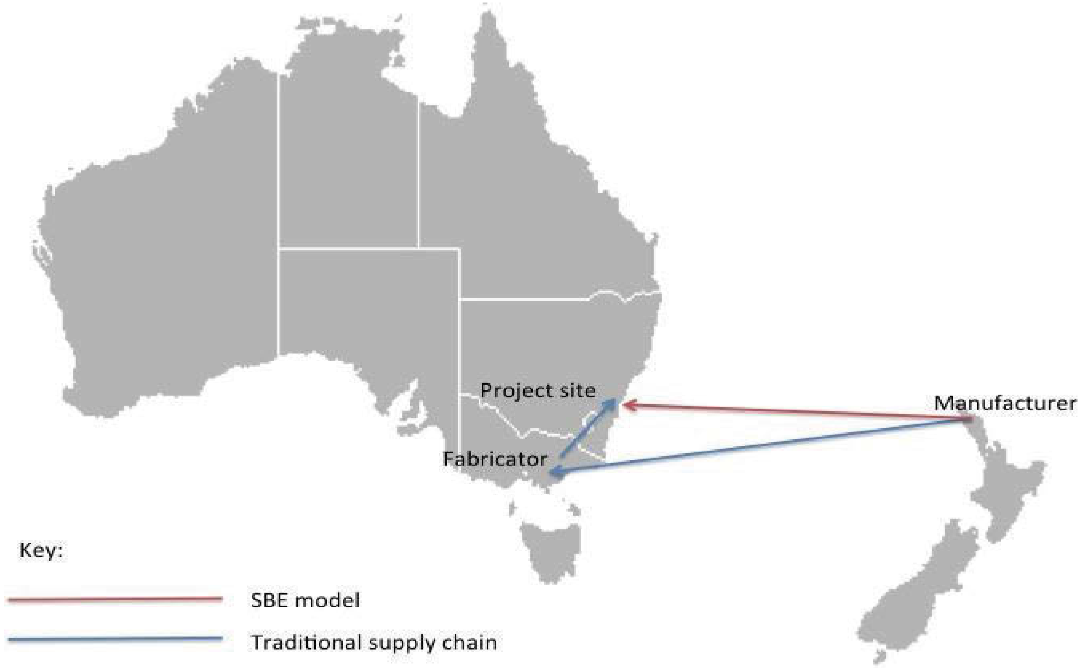

Figure 9.3 Case study supply chain route to project site

COST COMPARISON

As detailed in Figure 9.2, a total of 11 gravity frames were used in the case study building, with a total of 726m^3 of LVL b – with each gravity frame having a total of 66m^3 of LVL prefabricated timber elements, including columns and beams (further details on breakup of components are available in **Appendix F – Virtual building case** study used to test SBE model). The figures in the cost analysis in Table 9-2 below were obtained from case study data from earlier in this chapter. This cost analysis is divided into three main areas; material supply, design and installation. Cost comparisons and discussions are performed for these areas.

1. **Material supply costs**

Table 9-2 Case study building cost comparison, traditional supply chain vs SBE model

Item	Traditional supply chain	SBE model
LVL input costs	$1,300/m^3	$1,300/m^{3*}
Fabrication costs Inc. labour	$400/m^3	$300/m^3
Preliminaries & profit	$300/m^3	$200/m^3
Transportation	$263/m^3	$120/m^3
TOTAL per m^3	$2,263/m^3	$1,920/m^3
TOTAL for whole structure	$1,656,516	$1,405,440

* More opportunity to control LVL input pricing

LVL input costs

Under the traditional supply chain the manufacturer doesn't have a close relationship or alliance with the fabricator. Moreover, as established in Porter's 5 forces analysis in Section 7.4, the LVL manufacturer (supplier) has a lot of power over the fabricator, as there are limited manufacturers and the LVL inputs make up a substantial amount of costs. Under the SBE model, when the manufacturer integrates downstream into fabrication, they have more control of these input costs and, as the SBE model also interacts directly with the head contractor, they have the opportunity to lower these input costs when necessary to win projects. Thus, if they have excess supply at a certain point in time, they can take advantage of this and go in with a competitive price against steel and concrete alternatives to win projects in the non-residential market.

Fabrication costs including labour

Under the SBE model there is a potential to save costs. As manufacturers have the size and capital to set up an efficient fabrication processes, this fabrication process can be set up as separate job shop within the manufacturer's facilities, similar to large glulam and CLT manufacturers throughout Europe, where one part of the business manufacturers bulk commodity items and another part focuses on fabricating ETO systems for specific projects.

Preliminaries & profit

Having the SBE model undertake fabrication work leads to a number of savings as a second company doesn't have to undertake this work. Figure 9.4 presents various costs associated with manufacturing prefabricated timber systems. Having the manufacturer undertake both fabrication and manufacturing work under the one roof and not having to have another company perform the fabrication work leads to savings across various areas including: rent, utilities, depreciation, other costs and wages. These costs are not eliminated altogether under the SBE model though they are reduced by approximately 10%, which leads to cost savings.

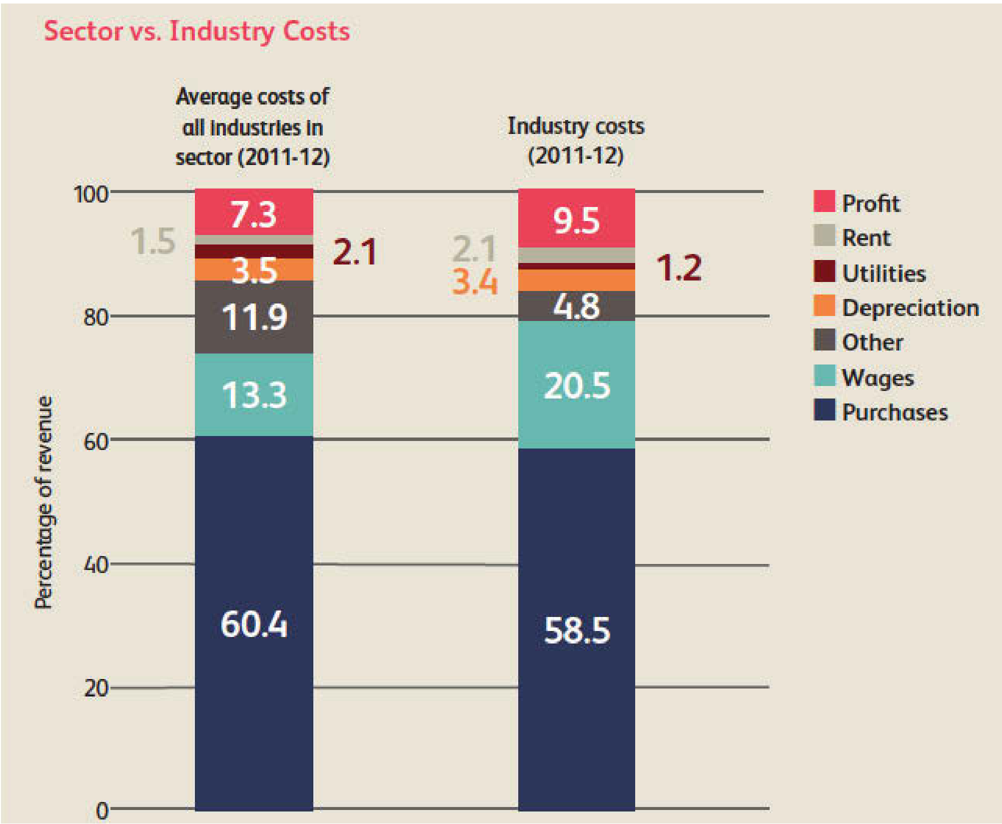

Figure 9.4 Fabricated wood manufacturing in Australia cost structure benchmarks

Source: IBISWorld

Transportation

There are transportation cost savings under the SBE model, as a lot less double handling is involved. As shown in Figure 9.3 under the SBE model the prefabricated timber elements get transported directly from NZ to Sydney. Under the traditional model the LVL elements would be sent from NZ to Melbourne and then onto Sydney. This leads to extra costs and also time which will covered in the following section.

Table 9-3 Shipping costs NZ (Marsden Point) to Australia (Sydney/ Melbourne)

Description	**Unit**	**Charges ($AUD)**
Exworks Charges	Per 20ft Container	$1720.00
Ocean Freight	Per 20ft Container	$650.00
Port Service Charges	Per 20ft Container	$520.00
Shipping Documentation Fee	Per Bill Of Lading	$85.00
CMR Fee	Per Bill Of Lading	$25.00
Delivery Order	Per Bill Of Lading	$55.00
Sea Caro Automation	Per Bill Of Lading	$20.00
EDI & Security Fee	Per Bill Of Lading	$23.50
Customs Clearance	Per Customs Entry	$135.00
Quarantine Assessment Fee	Per Entry	$25.00
Sideloader Delivery(Metro Approx)	Per 20ft Container	$500.00
Fuel Surcharge	14.5%	$72.50
Container Booking Fee	Per Container	$40.00
Sideloader Surcharge	If Applicable	$75.00
	Total	$3,946.00

Source: a. hartrodt Australia Pty Ltd (quote)

Total Cubic = 32.7 Cbm of each shipping container

Total transportation cost approx. cost per m^3 = $120 (used in table 9.2)

2. **Design costs**

Design costs and potential savings are less tangible to measure compared to material supply costs. Being an ETO product the design stage is an important process as each prefabricated timber system undergoes this process. The one key benefit that the SBE model has is that the designer - in particular, a structural engineer – even though outsourced is part of the SBE under an alliance arrangement. This helps ensure the designer is aware of the fabricator’s abilities and can design structural elements accordingly. This addresses a number of issues highlighted throughout the building case studies, where there was fragmentation between the designers and the manufacturers/fabricators. Strengthening the relationship between these parties can lead to cost savings in future.

3. **Installation costs**

Similar to design costs, due to lack of data it is difficult to tangibly measure the benefits of the installation time and cost savings under the SBE model as against the traditional supply chain. Though learning from experiences in Europe where CLT companies have alliances with installation companies, as more projects get built and the installers become specialists in the installation of the specific prefabricated timber systems, time and cost savings can be accrued. Under the SBE model having an alliance with an installer will help drive efficiency over time as more projects get completed.

TIME COMPARISON

As shown in Figure 9.3 under the new SBE model where manufacturing and fabrication is undertaken at the one place, complete components can then be delivered straight to the project site in Sydney. This saves the time associated with sending blank LVL billets to a fabrication workshop in Melbourne and then having to deliver these products again from Melbourne to the project site in Sydney. The shipping time from New Zealand to Sydney/Melbourne is the same at 7 days in transit. The key benefit of the SBE model here is that both the manufacturing and fabrication is performed at the same premises in New Zealand and then complete systems are shipped to the port closest to the project site i.e. Sydney in the virtual case study. This saves the issues of having to ship LVL billets from NZ to Melbourne for fabrication and then having to transport these by road up to the project site in Sydney.

QUALITY COMPARISON

Under the SBE model there is potential to improve the quality of the prefabricated timber systems in the building case study in a number of areas.

Firstly, transporting complete systems directly from NZ to the project site in Sydney reduces the chances of materials getting damaged during transport. As highlighted in building case study 1 - UTS floor systems - materials were damaged during transportation as a result of lack of communication between manufacturer and fabricator. This can be potentially alleviated through the SBE model due to the manufacturer and fabricator being the same entity and also, with the SBE model having a direct relationship with the project site and head contractor, it being in their interest to ensure materials arrive on-site at a high level of quality. Secondly, as the manufacturer has the size to set up a capital intensive and efficient fabrication process, there is potential that the quality of fabricated elements is better than the traditional supply chain. In particular, where glulam manufacturers undertake the fabrication process, there have been issues with glue lines and gaps forming in projects i.e. NMIT.

9.3 Conclusion

Findings from case studies in Chapter 8 lead to some changes to the SBE model developed in Chapter 7, Figure 7.4. These modifications were highlighted in section 9.2.2 Modifications to the SBE model to incorporate findings from part two building case studies. The key changes were around the LVL manufacturer integrating downstream into fabrication of EXPAN components. This was brought about by a number of time, cost and quality issues associated with the current supply chain. Then, following on from this, Section 9.2.3 How the SBE model can improve time, cost and quality, outlined through a hypothetical case study how the SBE model has potential to improve the cost, time and quality associated with the procurement and delivery of EXPAN systems. As there have been no buildings using EXPAN systems in Australia to date, a hypothetical case study was used, and in turn has some inherent limitations due to assumptions and data used.

Chapter 10 Summary and conclusions

10.1 Introduction

This thesis studied how the organisations along the supply chain impacted on the time, cost and quality of prefabricated timber systems in the construction industry. The research drew heavily on the themes of SCM and sought to address a gap in the literature around how the supply chain for prefabricated timber systems impacted on their viability. The research drew heavily on the concepts of SCM with a specific focus on strategic procurement and its application to structural contingency theory. This summary and conclusion chapter will cover a number of key areas, including firstly a brief summary of the research, a review of the aims and objectives, some limitations of the research and finally recommendations for further research.

10.2 Summary of research

This research started by establishing a number of research gaps, which lead in research questions. Then an in-depth literature review was undertaken looking firstly into the concepts relating to different organisational theories. After reviewing different organisational theories, structural contingency theory was selected as being relevant to this research, in particular, its application to SCM. Following on from this, the different concepts relating to SCM were critiqued, and strategic procurement was selected to the application of structural contingency theory to prefabricated timber systems. Finally, the various prefabricated timber structural systems were reviewed, highlighting the established mature market for prefabricated timber systems in the European market as well as their barriers to entry in the Australian and NZ market.

Case studies interviews were then undertaken with industry practitioners in Australia, NZ, Finland, Germany, UK and Austria. These interviews uncovered the various issues along the supply chain for prefabricated timber systems. The structures of the organisations along the supply chain were looked at in detail. Findings from these case study interviews highlighted that businesses in Europe had vertically integrated company structures, which were a result of a mature market for prefabricated timber systems. This is in stark comparison to timber companies in Australia and NZ, where there is limited use of prefabricated timber systems in large multi-storey buildings. Due to these market forces, companies along the supply chain are fragmented and lack the vertical integration that has succeeded in Europe.

Analysis of the case study interview findings combined with concepts of SCM and structural contingency theory was used to develop a strategic supply chain model – the SBE model. A deductive research method using structural contingency theory was adopted to help develop the supply chain model. A Porter's five forces analysis as well as a detailed analysis of the needs and expectations of clients in the non-residential construction market helped supplement and support the model. The key aspects of the model were increased collaboration among companies along the supply chain through the use of strategic alliances and partnerships. This increased collaboration is aimed to help improve communication, decrease fragmentation and provide a more cost and time efficient value chain for prefabricated timber systems.

Three building case studies – two in NZ and one in Australia, were used to test the structural contingency theory in relation to the supply chain for prefabricated timber systems. A seven-step framework and the pattern matching technique were used to test structural contingency theory. All of the three building case studies confirmed the hypothesis as the expected patterns and observed patterns matched in all cases. The three case studies also highlighted a number of time, cost and quality issues that occur along the supply chain for prefabricated timber systems. Similar to the findings from interview case studies, issues highlighted were along similar themes including lack of communication and collaboration amongst supply chain members, lack of fabrication capacity, and lack of design expertise.

Finally the SBE model was verified through the use of a hypothetical building case study. The building case study, although hypothetical, was able to demonstrate how the SBE model developed in Chapter 7 can be used to improve the performance (time, cost and quality) along the supply chain for prefabricated timber structural systems. In addition, following from further empirical evidence from building case studies in Chapter 8, the SBE model was modified to better suit the needs and expectations of end users, and help improve the performance of prefabricated timber systems through improving time, cost and quality issues along the supply chain.

The research has contributed to the body of knowledge on the supply chain of ETO products. No other study to date has looked into how the supply chain impacts on the performance of prefabricated timber systems. Through the use of interview and building case data, this research has been able to fill a gap in knowledge around how the issues along the supply chain impact on the performance and in turn commercial viability of prefabricated timber systems in an Australia and New Zealand (NZ) context. A supply chain model was developed and proposed as a means going forward to address these issues.

In order for the proposed model to become a reality the gap in the supply of the system for prefabricated timber systems must be addressed in order for the method of construction to become truly viable. The gap in the supply side is caused in part by a gap in the demand side, which has in turn prevented necessary investment into the capital and organisation structures required. As there has been limited demand for prefabricated timber systems in Australia and NZ, the supply chain for such systems is limited in capacity. There are a number of areas of future research covered in section 10.5 Recommendations for future research.

10.3 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:

Prefabricated timber systems have the potential to increase productivity in the non-residential construction market and provide a sustainable alternative to traditional forms of construction. While there has been some initial research, further work is required. In particular, it is important to understand how the supply chain impacts on the commercial viability of these systems and what can be done to improve the performance of these systems.

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

10.3.1 Investigating 'how' and 'why' the supply chain impacts on the performance of prefabricated timber systems

A preliminary literature review was undertaken followed by data collection of forty-two case study interviews undertaken with industry professionals across Australia, New Zealand, Austria, Germany, Finland and the UK. These interviews established the key issues along the supply chain that impact on the time, cost and quality (performance) of prefabricated timber systems. A cross case analysis was then undertaken to compare the issues between Australia and NZ and the European countries. From this cross case analysis it was identified that the structures (services offered and business models) of the companies along the supply chain have a significant effect on the performance of prefabricated timber systems, particularly in Australia and NZ where the market is in relative infancy compared to Europe. In Europe prefabricated timber structural systems are a more mature market, and for the past two decades have been used there in multi-storey non-residential buildings. Over this time, inefficiencies along the supply chain have been able to be addressed and, as demand and market size continually increased, the capacity and skills of companies along the supply chain improved. One key aspect of the companies in the European market is that over time they continued to become vertically integrated, with design, fabrication/manufacturing, detailing and installation all being offered to prospective clients. This offering of a complete solution to clients allows a lot of the issues currently present in the Australian and NZ industry, i.e. lack if fabrication capacity, fragmentation, limited design and detailing expertise, to be alleviated.

10.3.2 Examining 'how' and 'why' the structure of organisations along the supply chain impact on performance of prefabricated timber systems

This aim was achieved through analysing and undertaking interviews with senior management from fourteen timber companies – seven in Australia and NZ and seven in Europe. These case study interviews provided insights into how the companies along the prefabricated timber supply chain are structured and what services they offer. A cross case analysis was performed between the companies in Australia and NZ and then the companies in Europe. The key finding of the case study interviews and analysis was that the way the companies are structured is primarily dependant on market conditions. In Australia and NZ the supply chain and companies along it weren't structured in a way that best suited the non-residential market and its unique needs and expectations. The timber companies, primarily LVL manufacturers, were set up to service the residential construction market in which products are commodity in nature with very little value adding being undertaken as these products move downstream to the end customer. There is also limited communication between the timber companies and the end user. In the residential market (single storey housing) where products come in standard sizes and are Make-To-Stock (MTS) in nature, this lack of communication isn't a necessity. By contrast, in multi-storey construction, where prefabricated timber systems need to be designed and fabricated (Engineered-To-Order (ETO)) to meet the specific requirements of the particular building, collaboration with the architectural and design consultants is much more critical than for single storey residential housing. In Europe's more mature market, timber companies are vertically integrated and have the capacity, skills and expertise to meet the aforementioned concerns in the residential market in Australia and NZ.

10.3.3 Applying the concept of supply chain management to investigate issues of the supply chain for prefabricated timber systems

Azambuja & O'Brien (2009) developed a conceptual framework (see Figure 7.2) to model construction supply chains. This framework was used as a basis to support the development of a comprehensive supply chain model in this thesis – the SBE model.

The framework incorporated five steps:

1. Define supply chain model purpose
2. Supply chain performance measures
3. Determine product type
4. Define supply chain configuration
5. Characterise supply chain elements

These steps were used as a framework to develop the supply chain model in this thesis.

Moreover, after reviewing the SCM literature, four key themes were established, namely distribution, production, strategic procurement and industrial organisational economics. The strategic procurement perspective was selected as the key theme relevant to this research and of most relevance to improving the performance of prefabricated timber systems. The ideas behind the strategic procurement literature and structural contingency theory were also used to help support the development of the SBE model.

10.3.4 Developing a supply chain model – the SBE model

A key theme in the strategic procurement literature in SCM was to view the supply chain from a strategic perspective, through which supply chains began rethinking their organisational structure to suit the environment (Christopher 2011). This thinking stems from structural contingency theory – an organisational theory which states that there should be a fit between the organizational processes and the environment in which the company operates. The concepts of structural contingency theory around ensuring that company structures match the environmental requirements in order to achieve successful performance (Burns & Stalker 1961; Donaldson 2001; Lawrence & Lorsch 1967) were utilised when developing the supply chain model. The market needs and expectations of non-residential construction were covered in chapter 7 and then the ideas of structural contingency theory were adapted to the supply chain as a whole instead of to individual companies on the basis that the supply chain as a whole should be structured to suit the environment (Flynn, Huo & Zhao 2010). It was also important to consider how, in order to meet ever changing market demands, organisations have restructured to form a 'network', where the supply chain is an extension of the organisation. This was used to help support the ideas around the SBE model.

10.3.5 Verifying and testing of supply chain model

Three building case studies were undertaken to investigate the key issues along the supply chain that effect time, cost and quality. The pattern matching method was used to test the structural contingency theory's effect on the ETO supply chain. Applying the pattern matching technique, the predicted pattern and the observed pattern matched, which supported the efficacy of structural contingency theory.

All of the three case studies also highlighted a number of time, cost and quality issues that occur along the supply chain for prefabricated timber systems. Similar to the findings from interview cases studies, issues highlighted were along similar themes: lack of communication and collaboration amongst supply chain members, lack of fabrication capacity, and lack of design expertise. One key issue that was touched on in the interview case studies and really made clear in the building case studies was that companies along the supply chain were not being structured in a way that best meets the market needs and expectations of the non-residential market.

10.4 Limitations with research & SBE model

This research identify issues along the supply chain of prefabricated timber systems using data from case study interviews and building case studies in the non-residential construction market. A number of limitations of this research have been recognised. These relate principally to the case study interviews and the building cases and are broken up into a number of key areas including the case study interviews and building case studies and the SBE model.

Firstly, limitations are associated with the case study interviews in relation to the sample size and interview participants. Forty-two Round 1 and Fourteen Round 2 interviews were undertaken with industry practitioners across Australia, NZ, UK, Austria, Germany and Finland. One limitation of these case study interviews is that the issues established are limited to the experience of the interviewees – even though out of the fifty-six interviews conducted approximately 73% of interviewees had 20+ years' industry experience. The findings from these interviews were limited to the respondents' experiences. An increase in the sample size of interviewees from Europe, where more prefabricated timber buildings have been completed in the non-residential sector could have been more valuable to provide a more in-depth analysis of these issues. In addition, in Australia and NZ there has been very limited use of prefabricated timber systems in the non-residential market, so some of the interviewees may not have had sufficient experience working with these systems. Due to the lack of experience of some of the practitioners there is a potential that a number of other issues occur along the supply chain which might not have been identified.

Another limitation of this research is the data obtained from the testing of structural contingency theory in the building case studies. As very limited multi-storey non-residential buildings in Australia and NZ have utilised prefabricated timber systems it was difficult to obtain access to data from a large sample of buildings. Having only three building case studies in this research may have limited access to issues along the supply chain that affect time, cost and quality.

Similarly with the testing of the structural contingency theory, having the opportunity to test the theory on a larger number of case studies may have produced different results.

Even though the SBE model developed in this thesis is robust, it does have some limitations. Data from case study interviews, literature review and structural contingency theory were used as a basis to develop the model. This SBE model was then further refined through the use of the building case study data, where it was modified to incorporate the manufacturer integrating downstream into the fabrication stage of the supply chain. After reviewing literature it was established that this supply chain model is the first of its kind and unique to the Australian and NZ market. One limitation is that the model is focused towards the supply chain of EXPAN prefabricated timber systems and that it may not be as relevant to other ETO products. The limitations of the model overall are primarily due to its uniqueness, though the theoretical background underpinning the model can be adopted for all types of products.

There are other limitations with the SBE model developed in this thesis, primarily around demonstrating how the SBE model leads to time, cost and quality savings. In order to give some indication of the benefits of the SBE model over the traditional supply chain, this thesis used a virtual building case study to give some indication of the possible benefits of using the model. The data used to demonstrate the time, cost and quality differences came from a mixture of the real life building case studies in Chapter 8 and IBISWorld industry reports.

10.5 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 supply chain impacts on the time, cost and quality of ETO prefabricated timber systems. It is also the first piece of literature to apply structural contingency theory to the ETO supply chain and to test it. This research provides a good basis to build upon and there are future research possibilities to follow on from it. Section 10.2 discussed some limitations of the research and SBE 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.

10.5.1 Undertake further building case studies to determine issues along the supply chain that affect time, cost and quality

As outlined throughout this thesis there is a lack of multi-storey non-residential buildings in Australia and NZ that have used prefabricated timber structural systems. Section 5.5.1 highlights there have only been seven non-residential buildings to date that have used the EXPAN system, the system focused on in this research. Out of these seven buildings only three of them were multi-storey – with the others being single-storey. Moreover, the SBE model developed in this thesis is more suited toward EXPAN systems though it can also be adapted for use in other systems such as CLT another prefabricated timber system that has just emerged in the Australian construction market.

Chapter 8 highlighted findings from three building case studies, and albeit that this is a relatively small sample size, through the use of interviews, personal observations and documentation some rich data was able to be obtained on the issues along the supply chain that affect time, cost and quality. As more multi-storey non-residential projects are completed, it would be good to do further research on these case studies and determine further issues along the supply chain.

As more buildings get completed using prefabricated timber structural systems, it will be significant to conduct further research and establish whether the issues presented in Table 6-5 remain present as supply chain and industry capacity and expertise improves. Likewise, as industry and supply chain capacity improves, this further research will be able to determine if new issues are established. By increasing the sample size and studying further buildings there is potential to gain further findings on key issues along the supply chain, which can help to understand developing trends.

10.5.2 Undertake further analysis on completed buildings in Europe using prefabricated timber systems

Similar to and following on from the above section, undertaking case studies on completed non-residential projects in Europe will allow further issues and lessons learned to be established. Part one case study interviews highlighted key issues that occur along the supply chain throughout projects in Europe and Table 6-9 outlined the business models of timber companies in countries throughout Europe, including Austria, UK, Finland and Germany. Undertaking a further research piece looking into building case studies similar to the analysis done in part two of the research in Chapter 8 could help uncover some findings and lessons learned that could be useful for the Australian/NZ industry. In particular looking at some of the initial projects in Europe that used prefabricated timber structural systems, and progressively looking into projects as the technology unfolded, could provide a useful research piece for the Australian and NZ industry.

10.5.3 Obtaining feedback from companies along the supply chain on their interest to be involved & implement the SBE model

Prior to implementing and testing the SBE model on a real building case study, there is a potential research piece to be undertaken on obtaining feedback from companies along the supply chain on their thoughts on the SBE model. In particular, interviewing manufacturers to gauge their interest and willingness to help drive the SBE model is critical to its implementation. If these manufacturers aren't interested in adopting the SBE model and in particular setting up a separate business unit or division to liaise directly with the builders and head contractors in the non-residential market and integrating downstream into the fabrication space, the model's potential will be limited.

As part of this further research piece there would also be value in discussing with companies, both the original SBE model in Figure 7.4 and then the updated model –

Figure 9.1 in Chapter 9, providing details on how the original model was developed (through case study interviews, strategic procurement literature and structural contingency theory) and then outlining how, after the building case studies, the model was further modified to incorporate downstream integration into the fabrication space. Obtaining feedback from fabricators and manufacturers on which model they thought was more appropriate in the short term would be useful. In particular manufacturers may be reluctant to adopt the updated SBE model, which incorporates downstream integration into the fabrication space, if no market demand is present. Fabricators may also be reluctant under the original SBE model in Figure 7.4 to align themselves and be controlled by one manufacturer (SBE entity). It is important to discuss and obtain feedback from designers and installers on their views of the model, as under the SBE model installers loose a direct link with the head contractor, which they may or may not prefer. In Europe the large timber manufacturers deal direct with the head contractor and either perform the installation process themselves or sub-contract out and project manage the installation process. Obtaining feedback on these issues would be critical prior to implementing the model on a project.

10.5.4 Implementing and testing the SBE model on real building cases

Section 9.2.3 outlined how the SBE model has the potential to improve time, cost and quality of prefabricated timber systems compared to the traditional supply chain model. A lot of further research remains to do in this area, particularly in regard to implementing and testing the SBE model on a real building case study to collect empirical evidence to support whether the SBE model does lead to 'actual' time, cost and quality benefits. Undertaking research on projects where companies have adopted and implemented the SBE model will help establish and provide empirical data on the actual benefits to time, cost and quality that can be obtained over the traditional supply chain model. Finally, in future after the SBE model has been implemented and adopted in a number of projects, there is potential to undertake research and provide further modifications to the model.

10.5.5 Re-testing structural contingency theory on building case studies that have used the SBE model

In Chapter 8 each of the three building case studies tested structural contingency theory and the supply chain of prefabricated timber systems is the environment in which the theory was tested. As discussed throughout this thesis, structural contingency theory outlines there should be a fit between the organizational processes and the environment and that company models that match the environmental requirements should perform more successfully than those that don't (Burns & Stalker 1961; Lawrence & Lorsch 1967). When applying this theory to the supply chain the individual dimensions of the supply chain should be aligned in order to achieve the best performance (Flynn, Huo & Zhao 2010).

This research tested the proposition that when the supply chain structure for prefabricated timber systems didn't match the environment, company and in turn supply chain performance would be low. This was confirmed in all three building case studies, where various time, cost and quality issues occurred as a result of the structure of the supply chain not matching the environmental requirements. Following on from this there is a further research opportunity to test structural contingency after the SBE model has been implemented. Under the SBE model the supply chain is now structured to suit the environment and according to structural contingency theory the performance of the delivery of prefabricated timber systems should be improved compared to the traditional supply chain model.

10.5.6 Implement & test the SBE model on other ETO products

After the SBE model has been implemented and tested on prefabricated timber systems, there is potential for further research to adopt and implement the model on other ETO products such as prefabricated concrete elements, HVAC equipment, steel elements, elevators, turbines, nuclear reactors, semi-conductor tools and power distribution equipment (Elfving 2003). By undertaking this research, it can be established whether the SBE model has application to further ETO products and, if so, what needs to be modified or adjusted so the model is applicable to these products. Strategic procurement literature and the ideas behind structural contingency theory can be applied to all types of ETO products, though slight modifications may be needed for different products.

10.5.7 Compare time, cost and quality of completed timber buildings with steel and concrete alternatives

There have been a number of studies (John et al. 2011; John et al. 2009; Menendez Amigo 2010; Page 2006; Smith 2008 ; Wong 2010) that have looked into the time and cost of non-residential buildings using prefabricated timber systems as against traditional steel and concrete options. All but one of these previous research studies have focused on comparing virtual timber buildings with either a real concrete or steel building. The exception was John et al. (2011) which compared the costs of a real timber building (NMIT) to virtual concrete and steel alternatives. After reviewing there literature no studies were found in NZ and Australia which compared empirical findings from real completed timber, concrete and steel buildings. As more non-residential buildings are completed using prefabricated timber systems there is potential for further research in this area.

Part of this further research can expand on section 9.2.3 whereby not only comparing the costs of completed similar concrete, steel and concrete buildings but also establishing the key factors along the supply chain of these different structural systems that constitute the majority of costs and lead to the highest amount of time. From this further research there is potential to learn from the prefabricated concrete and steel supply chain, which is more advanced, and adopt and modify practices and strategies used by companies in these supply chains and incorporate them to make the prefabricated timber supply chain more efficient. Moreover, the further studies that are performed on actually completed buildings should lead to further benchmarking and a larger database on cost and time analysis that can be used by industry practitioners such as quantity surveyors, project managers, and so on to develop a better understanding of costs and time associated with prefabricated structures and how they compare to traditional alternatives. The goal of this further research is to build up enough data points from on cost data in particular to feed into industry wide cost resources such as *Rawlinsons Construction Handbook* and *Cordells* as there is a severe lack of data on prefabricated timber system in the resources.

10.6 Conclusions

This thesis has successfully examined the issues along the supply chain that affect the time, cost and quality of prefabricated timber systems in Australia and NZ, as well as a number of countries in Europe including, Germany, Italy, Finland, Austria and the UK. Case study interviews were completed with industry practitioners in these countries who are experienced in the development of prefabricated timber systems. Subsequent case study interviews were undertaken with senior management from a number of countries along the supply chain in order to establish why organisations are structured they way they are.

A supply chain model – the SBE model – was developed for prefabricated timber systems in the Australian and NZ market as a way to address the various issues highlighted in the case study interviews. Strategic procurement literature, structural contingency theory and lessons learned from the mature European market helped to support the development of the SBE model. Building case studies were then used to test structural contingency theory in relation to prefabricated timber systems. Following on from these case studies and more data, further refinements were made to the SBE model to help better suit the Australian and NZ market.

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Appendices

Appendix A – Interview consent authority form

UNIVERSITY OF TECHNOLOGY SYDNEY

UTS:DESIGN, ARCHITECTURE & BUILDING

I ______________________________ *(participant's name)* agree to participate in the research project ***Supply Chain Management - Strategies for multi-storey timber construction in Australia and New Zealand*** being conducted by PhD student Matt Holmes Faculty of DAB, matt.holmes@uts.edu.au, (contact no. 0422 189 399), who is under the supervision of Grace Ding, grace.ding@uts.edu.au (contact no. (02) 9514 8659).

I understand that the purpose of this study is to develop supply chain integration strategies for multi-storey timber construction in Australia and NZ. I understand my selection to be interviewed is due to my experience in multi-storey construction and or the timber industry in Australia and NZ.

I understand that my participation in this research will involve a personal interview for about an hour or so to answer questions in relation to multi-storey timber construction industry in Australia and NZ and to outline how the supply chain impacts the feasibility of such buildings. The information from the interview will be solely for this research purposes and will be kept confidentially in all publications.

I am aware that I can contact Matt Holmes or his supervisors (Grace Ding, grace.ding@uts.edu.au or Keith Crews, keith.crews@uts.edu.au) if I have any concerns about the research. I also understand that I am free to withdraw my participation from this research project at any time I wish, without consequences, and without giving a reason.

I agree that the research data gathered from this project may be published in a form that does not identify me in any way.

______________________________ ____/____/____

Signature (participant)

______________________________ ____/____/____

Signature (researcher or delegate)

NOTE:
This study has been approved by the University of Technology, Sydney Human Research Ethics Committee. If you have any complaints or reservations about any aspect of your participation in this research which you cannot resolve with the researcher, you may contact the Ethics Committee through the Research Ethics Officer (ph: 02 - 9514 9772 Research.Ethics@uts.edu.au), and quote the UTS HREC reference number. Any complaint you make will be treated in confidence and investigated fully and you will be informed of the outcome

Appendix B – NVivo 9 node report

Node Summary

PhD Case Study Interviews R1 Australia/NZ

Source Type	Number of Sources	Number of Coding References	Number of Words Coded	Number of Paragraphs Coded	Duration Coded

Node

Nickname: **Nodes\\Building code requirements**

Classification:

Aggregated: **No**

Document	6	16	480	49	

Nickname: **Nodes\\Design and detailing**

Classification:

Aggregated: **No**

Document	9	19	433	33	

Nickname: **Nodes\\Fabrication**

Classification:

Aggregated: **No**

Document	15	64	1,749	78	

Nickname: **Nodes\\Fragmentation along supply chain**

Classification:

Aggregated: **No**

Document	12	28	862	35	

Source Type	Number of Sources	Number of Coding References	Number of Words Coded	Number of Paragraphs Coded	Duration Coded

Nickname: Nodes\\Installation capacity

Classification:

Aggregated: No

Document	8	14	334	20	

Nickname: Nodes\\Logisitics transportation between stages

Classification:

Aggregated: No

Document	2	2	18	2	

Appendix C – Interview transcript example – R1 Australia/NZ

Key:

J = Interviewee (Consultant)

M = Interviewer (myself)

J: Should, we get into and start to answer the questions.

M: I made a number of questions for people who have experience in the timber industry to get an idea of peoples views on the issues in the supply chain.

Then from there I've focused mainly on the fabricators, manufacturers, distributors really just to get more understanding of what they do, the markets they operate in and their business models, how big they are, what are they planning to do going forward. Are they interested and things like that.

J: Yep, I just went through your presentation again as well, your PowerPoint slide show and you've picked up a lot of very good points already. I'll do my very best to add a bit to that.. I've got some very strong views on some of the industry issues so... I'll let you know about these I guess.

M: No worries, are these just views on companies involved?

J: No not particularly companies, ahh......... coming from Europe I think I see some of the short-comings from the industry down here, what is missing yeah?

M: Yeah, yeah

J: And ah some how the local industry doesn't seem to pick that up for what ever reason or doesn't want to see it and recognise it. But you've picked up on it with your work there already, so good on Europe.

M: Yeah but it's weird for me after visiting Europe and then after first time I went to NZ and visited NMIT it seemed so clear that they had to follow a similar model to what the Europeans do essentially and it seemed simple..

J: Yeah, yeah

M: Well to me anyway

J: Well you clearly see something that many other companies and people in that space don't see, so ahh keep going on with that.. Good on you… So how do we do that just one by one through your questions or??

M: Yeah that would be great if that's OK?

J: Yep, that's absolutely fine. So if I start off, I read through your questions yesterday and took some notes down to get some ideas sorted.. So lets begin.

M: Are the manufacturing capabilities of the EWP producers, i.e. LVL and glulam limiting the feasibility of multi-storey timber building in Australasia?

J: Well I think it's important to distinguish the difference between the raw material producers and the fabricators yeah?

M: Yes, I agree,

J: So... for example Manufacturer 1, Manufacturer 2 and Manufacturer 3 the guys making the LVL are making the raw material and this is then picked up Fabricators, who then turn that into the timber building system… So to answer your question there I don't think the raw material suppliers as in the raw material suppliers, or their manufacturing capabilities are an issue. Though it's more so the fabricators that's the issue...

M: Yes, I agree and the main point of that particular question was to get peoples feedback/clarification as to whether they think the actual manufacturing is an issue. A lot of people have tended to agree with that and I wanted to see if that was a common consensus amongst most.

J: Yep, it's the fabricators that the key issues and not so much the manufacturing... I look at the wood industry in New Zealand and Australia and I see that these two countries are good at milling trees and turning it into sticks of lumber, plywood, LVL - making a commodity out of it. But then it just stops. There is very limited capacity to then take this forward.

M: Yeah there doesn't seem to be many people that can then turn this into a building system

J: Yes, that's where the big gap is... Turning this commodity product into a complete building solution to clients.

M: But I guess on that point too though there's been no market for that to occur.

J: Yeah, yeah,

M: So the LVL manufacturers business models are essentially risk free, they don't have to worry about issues with individual projects per say... In the residential market they just pump out billets and then ripping them up and sending them up to distributors...

J: Yes, and that ripping of a commodity and sending it on, is something very different producing a building system to meet a certain clients requirement and to comply with certain codes yeah, it's a totally different thing.

M: Yeah, agreed and it's determined by the particular market. I mean the residential market is very different than the commercial market.

J: Yeah, and the other thing which you've just mentioned which is a very good observation is umm there hasn't really been a market for multi-storey timber buildings. Though suddenly because of developments like EXPAN and CLT and all these trends, and suddenly the market is screaming we need all these multi-storey timber buildings. Though the market can't suddenly turn around and deliver that... So that's the challenge for the fabricators I guess, how do they ramp up there capacity and their quality as well.. Because if you look at the quality they have been producing it's really not good enough for the multi-storey timber buildings, the tolerances and all of that...

M: Yeah, especially when they're prizing on aesthetic qualities and it's exposed.. But I guess the costs that's needed to get that aesthetic quality that is required as well as a show piece is difficult.

J: Yes, depending on what type of finish you want can lead to extra costs.

M: Next question, do you think the fabrication is an issue and if so going forward who do you think will be the people taking this forward in the future?

J: Yes, as we've discussed it's the fabricators that's the issue.

M: Yes, agreed and what are your thoughts on someone like Manufacturer 1 and Manufacturer 2 vertically integrating into fabrication?

J: Ahh that's an interesting one!

M: That's what I've been trying to say to them, though I understand it's a very different business model to what they've got at the moment.

J: Ahh, it's an interesting one, and I don't think you can generally answer it with - Yes they should move into that space, or NO they shouldn't... I see the interest they have in that, and I think if they don't venture into this themselves they should at least partner or form a close relationship with a fabricator in that space. I mean they do that already to some extent where Manufacturer 1 already works closely with Fabricator 1… Umm but you could ask the question should Manufacturer 1 and Manufacturer 2 themselves start to do fabrication?

M: And I know from the people I've spoken to at Manufacturer 1 and Manufacturer 2 they've looked into the feasibility of doing it.

J: Yeah… ummm

M: From the literature and their feedback at the end of the day it's most probably going to require a separate company/business within their line.

J: Yeah exactly it would be a separate business which is an offshoot of Manufacturer 1 or Manufacturer 2 umm it's perfectly doable.. Though what's really required there, and it doesn't matter who does it - whether it be the manufacturer or the fabricator or an investor from the left field, who just sees an opportunity in that space…

M: I was thinking which may be a bit political though the steel industry might be able to provide the solution... I mean they provide that model where they can at least offer a solution… Where they fabricate, design and install.. I mean they are just providing a service so what's the difference whether they are using timber or steel.

J: I mean they have experience with that process already; it's just using a different material.

M: It's more so the service they offer as opposed to solely the material.

J: Yeah that's the right, and the KEY POINT is no matter who does it, i.e. steel industry, timber industry or an investor form left field, or an existing fabricator.. The KEY is and I don't think this is really understood in the industry in this part of the world is that if you decide to go down that road you carefully engineer your fabrication operation around a defined set of products... This sounds very abstract now though usually whatever happens is if you have a company over here interested they go to a machine supplier, and they ask how much is the latest CNC machine and how much money do we have to spend to get into that. What inevitably happens they start looking at a prefab operation that does not necessarily suit them though they don't realise it because they engage straight away with the machine supplier... The issue is the machine supplier has a vested interest in selling a certain solution though not necessarily the solution that suits the fabricator.. You know what I mean?

M: Yeah, yeah

J: So that's the dilemma, in NZ anyway.. Now I was at FRAME conference last weekend and I did notice that ah...

M: Yeah how was that?

J: Yeh it was good, and there was a big BUZZ about that panelised prefabrication and that it will play more of role in the future.. Though that remains to be seen in whether people going away from that conference will actually take this and do something going forward.. They might not do anything and it was just talk and no action. Hot air so to speak.

M: Did you speak to many people from over here in Australia about fabrication?

J: Yeah from Australia, I had a couple of good conversations and it remains to be seen what comes of that. But the key is, the key is if you're interested in that space that you first carefully define what is it that you're trying to make, how long are these EXPAN components you would like to make, are they 10m or 20m? Do you want to be capable of doing 30m? What sort of cross sections - the smallest cross section, the biggest cross section.. And a few other things you really have to define first.

M: So it's really about clearly defining what markets you want to enter first - if you want to focus on portal frames you're going to set up different operations than if you want to set up post & beam frames or floors..

J: Absolutely, absolutely you may want to be able to do the whole range, though the main thing is that you first off clearly define your market, the products you want to produce and then you can set up your prefab operation to suit.

Once you've got that down on paper, and that stage is a lot more detailed and takes a lot more time than a company would typically believe… once you're got that, then you can sit down and work out how are we going to set up prefabrication process/business to deliver these products - can we do it manually or is their automated, what exact equipment would I need..

M: So they are going ahead gung ho with out actually knowing what they want or defining their markets.

J: Exactly, exactly... It really difficult for the manufacturer or supplier to serve the fabricator as he doesn't know what he wants to make… So it sounds very trivial and very common sense though the industry isn't defining exactly what they want to cover first and then engineering a prefab operation/business around that..

M: As opposed to setting up something, and then waiting for projects to come in and hoping that they matches...

J: Yeh, yeah exactly and hoping that it matches and in reality that if they go and just buy some kind of kit and start production and then realise that doesn't do what I want it to do..

I've been sitting around a boardroom table over here in NZ where a large wood company was looking to start to manufacture/fabricate CLT, STIC etc and they were asking me what do we need, and tried to squeeze out of me what do we need, what do we need, what sort of equipment do we need... And I tell them well, let me know what kind of products you want to make and I'll be able to tell you what you need.. but unless you actually define exactly what you are trying to make I can't tell you what you need.. It's unbelievable, I mean even large companies they really operate like that..

M: So it's more it's more of a push system as opposed to a pull system… Where as it should be a more of a pull system and they should be really defining who their customer is, what products they want to deliver to this customer and gearing up what they want to do…

J: Yes, really developing a business plan, and define the product and customer first - before they set up an operation. And by define I mean are we working with LVL, or LVL and glulam and what sort of cross-sections are we dealing with. What is the minimum and maximum dimensions we want to process. I'll bring that contrast in now, in Europe this method and this method of engineering a prefab operation is a lot more widespread and a lot more common and well known. in fact there is around a dozen universities in German speaking Europe (Germany, Austria, Switzerland) where all they do is, is train dedicated process engineers or industrial engineers and all they do is engineering and prefab operations... Where they are just working on the prefab business operation. They are not structural engineers, and they aren't machine operators, they are more developing business operations to suit a particular company/client depending on what type of product they want to produce. Because a successful prefab operation always needs to be tweaked and its a constant improvement process, so that's really, and sorry to ramble on... and this is one of my major messages when I engage with industry and it is don't just go out and do something for the sake of doing something because you think it's a good idea... Clearly define what you want to do and then go about setting up an operation to deliver this.. Sometimes the answer is we don't need CNC machinery because the quantities we are targeting don't justify it.

M: I think the biggest thing with screwing and gluing and re-laminating is the time and labour consuming process as there isn't an automated process for that is there?

J: No. Well screw gluing is another option for those who aren't interested in trying to glue laminate LVL they can try to screw glue LVL.

M: I wouldn't say its the most cost effective option.

J: I guess it really depends on what you are making, some have been successful in doing this.

M: On a bigger project though it looks like it may not be the most cost effective option. I was under the understanding that Fabricator 1 isn't able to re-laminate large column/beam cross-sections.

J: Have you confirmed that with Fabricator 1?

M: No I will though. For box beams you don't need a glulam press do you?

J: If by glulam press you mean hydraulic presses, then no. You can use traditional glulam presses with bolts and strong backs – 24 bolts with strong backs. The other one was done with airbags where they essentially use fire hoses that inflate and work well.

M: That cheaper to do it that way?

J: you can't necessarily say it's cheaper or not as it depends on how productive your pressing is and your entire operation. How many of these are you producing is it just the odd beam or are you producing a hundred of them, also the geometry of the components as well, you know umm if you're dealing with odd geometries that are really different to handle in a workshop environment. There are a number of variables. Horses for courses really. Well prefabricators and partnerships with the manufacturers. Ideally the model of having design and build under the one roof is quite interesting and effective, I mean this is ideal because he can experiment and try different things in his workshop that others cannot. The design and build is a really interesting model and you see it a lot more in Europe but umm obviously this not going to happen on a large scale in Australia and New Zealand as there just isn't the market for it. Design and build is interesting in that it gives peoples options that other don't have. But if design b and build is not an option and obviously partnerships between a manufacturer, fabricator and structural engineering office are important. Collaboration is important and umm STIC is the prime example that collaboration can produce great results, I mean you look at 3 competitors that have essentially collaborated with one another and pulling their resources together.

M: One idea I had was to have the large manufacturers driving it, as the smaller fabricators don't really have the capacity to do effective business development and if you one of the large companies to drive it and set up a consortium.

J: Yeah,

M: And they kind of come under this wing,

J: It's interesting I really have to think about it. What I mean by STIC is good model for collaboration is that they have to development the STIC IP in the first place and all the design guidelines that they are bringing out and all that, and they had to team up and pull all their resources together - that's great though where do they take it from here... well... I'll have think about what you've just suggested as it's quite a different model... but for example they actually become a fabricator, well why not, why not, if they can make a business case for it and convince themselves that there’s a market a there.

M: I mean the bigger contractors like to deal with a bigger entity down the chain,

J: yeah

M: Especially on a bigger project. What size projects do you think are feasible i.e. post and beam. I mean NMIT is only like what 900m^3 3 storeys. How big do you think is capable, much bigger than that?

J: You're talking about the structural system or the fabricators?

M: I mean both combined to deliver a competitive system.

J: I mean structurally the system used on NMIT or the STIC system there’s no reason to believe why it won't work up to 10 storeys I believe.

M: Not so much the design - more so the fabrication

J: Yeah, yeah you're right I mean if there was a bigger player there capable of working on bigger projects that would be good, yeah - I mean I wouldn't like to test Fabricator 1 or Fabricator 2 where their limits are, I mean if it was much bigger than NMIT they would struggle.

M: I mean it was clear that NMIT was a struggle, and that was with the manufacturer, fabricator and project in the same town.

J: Yeah, yeah you're right

M: So you think about in Australia if there's a project in Sydney, where we've already had issues getting LVL from Manufacturer 1. There are already issues just with the LVL supply. So you think on a bigger project the potential logistics issues, storage etc

J: So... what's your answer to that. To just get fabricators with a bigger calibre interested in the product?

M: Either fabricators, F&T people a few of them have shown interest, or they've got bigger capacity

J: That is interesting that they are interested in that - I'm surprised by that.

M: I wouldn't say that all, it is only been a few I've spoken to.

J: The reason why I'm interested in this is because they produce a commodity as well, and their systems are very well set up to take this system from design all the way to the market and its not yet the case - but yeah if they want to explore it, then why not.

M: From a few that I've spoken they are putting together a few rough costs, on what it would cost to fabricate floors etc.

J: Well I hope they do it the right way around, because I suspect they probably go to suppliers and ask how much is your CNC cutter and how much is this and how much is that.

M: It's still very early days and I wouldn't say they could deliver a project now though they are actively investigating it, and because just as a way to not be so reliant on the residential market.

J: OK

M: Moving along to the next question, is there adequate design expertise in Australian and NZ industry? If not how do you think this issue can be addressed?

J: Now there's obviously not enough timber engineering expertise in Aus or NZ, so there's definitely need to change that and up skill the engineers. I'm not just talking about structural, but also acoustic and thermal. Simply because as you get in multi-storey that is critical.

M: For fire and acoustics especially trying to get code approval.

J: There other interesting thing is that in the English speaking world the training system used to teach engineers the disciplines are very well separated - structural, civil, fire so on, very often they are living in silos and not really talking to each other - though in German speaking countries there are broader based engineers, where multi-storey timber buildings are designed and engineered in multidisciplinary office. Where if you look at a CLT building the structural goals are directly competitive with acoustic from a structural point you want the slab to continue though from an acoustic point of view you want the floor to be separated at the inter tenancy wall.

M: Then how your Mechanical and Electrical services integrate into that is a big thing - particularly with CNC routing and any passages used for cabling is important.

J: An engineer from Sydney mentioned that as well. I think they did some work on CLT recently. I guess it is what we have to live with.

M: As part of STIC no one has really looked at how the facade connects to the structure. What's the pull out force etc. There's still a lot to be done in that area..

J: The problem is what do we need to move first - the fabrication, designer, etc i.e. is there one bottle neck or a number.

M: I think at the end of the day its fabrication as it comes down to cost and time and there is some is some experience in design. Have you designed many buildings in NZ?

J: We have done a couple – I worked together with a formal colleague of mine on structural timber engineering, though there is only two of us so there is a type of limit on the size of project we take on

M: Would you design NMIT building?

J: No, I would not go above 3 storeys and NMIT is probably to large in scale - this is governed on the fact there is only two of us for now and as you get into the bigger structures they get complex very quickly from an integrated services point of view. So most of my time so far is spent on consulting to the prefabricating industry on how to prefabricate - so the goal is through management consulting I help the fabricators become more productive and use modern prefabricating technologies and then long term make the move to structural design. I agree with you that fabrication is the bottle-neck in the supply chain.

M: For NMIT it takes them 1.5 days to manufacture 400m^3 of LVL and close to 3 months to fabricate.

M: Are building codes an inhibitor in the uptake of timber buildings? If so what are the best ways to address these code issues?

J: I guess there are two aspects 1. Timber in the codes as it already exists and in NZ these are out dated i.e. in NZ the timber design code NZ standard 3603 is out dated as it goes back to 1993. So yes they are outdating and need updating. The next issue is codes that are non existent because we are dealing with a new product and compliance documentation doesn't exist so to speak, which is a big problem as well because very often when it comes down to making decisions for and against a building system. Developers are looking for the track record and if a system doesn't have track record and has a little bit of risk associated with it because it doesn't have compliance documents they will potentially shy against it. STIC has commissioned the durability guideline which is the design guide for durability for STIC or EXPAN structures.

M: has that been released yet?

J: No I do not think it's been released yet.

M: Does that take into account termites - are termites an issue in NZ?

J: No. No termites in NZ. That's actually been an interesting one because we've been pushing LVL into an area where it hasn't been in the past - how durable do these structures have to be and what are the design requirements or what is design expertise needed to demonstrate it is compliant or fit for purpose. So yeah there are code limits I would say.

M: Do you think fire and acoustic are limitations?

J: Yes, you can't go through the codes in the normal path - alternate solutions are time consuming and expensive. It just gives a natural advantage to systems i.e. steel and concrete that has a track record. For a developer that wants to minimise their risks. With the building codes it's all about giving confidence to the designers, specifiers and developers. If the codes are out dated or are non-existent and you need an engineered or alternate solution, that's just not ideal in giving confidence.

M: It is a similar kind of issue - chicken and egg, where this will only come with the demand

J: The first developers are pioneers and take the risk and want to try something new.

M: Question 5 - Which on-site trade do you see most responsible for installing prefabricated timber options?

J: There is a need for that and if it is not the fabricator itself, which is not necessary.

M: Do you think the fabricator should be Project managing the installation?

J: I think its an advantage - for example in the UK they do supply material, design and installation services. They say it gives them an advantage that others don't have.

M: Because I noticed in Europe some companies were responsible for the install and others contracted it out to another company - is that common in Europe, where the large glulam guys don't do it themselves they are essentially project managing it.

J: The goal is to have a kit set so well defined that you minimise the time required on site. Also the simpler it is the less thinking is required on site. The benefit is to have high quality prefabrication.

M: So essentially a steel rigger could be used.

J: Yeah, exactly someone who is experienced in installing larger members.

M: Some of the manufacturers were thinking carpenters though I don't think they are geared up to that sort of the installation (scale) - do you have an opinion on this?

J: Yeah I agree with that - carpenters should stick to their hand power tools.

M: Question 6 & 7 - What is the nature of firm relationships along the SC - are they typically adversarial or cooperative? Do they typically work well together and form partnerships and alliances. They power relationship is then a follow on from this, i.e. who has the power and who has the bargaining power for costs if they do have adversarial costs. For example because they're not a manufacturer they can go to who ever they want even though they've got their preferred suppliers - when a project comes along they can go to a number of manufacturers and tender it out. I mean is it like that.

J: I see where you're coming from - translating that question into the STIC world. That wouldn't be practical for the two fabricators in NZ to approach Manufacturer 1 and ask for a competitive price - you would use Manufacturer 2 because they are just down the road.

M: Do you do much work with the distributors in NZ?

J: Distributor being?

M: The distributor being the person in the supply chain between the manufacturer in the timber merchant.

J: No, no I haven't done any work with them and I don't know what I should be doing with them.

M: No I agree I was just wondering if you've done any work with them. I was just wondering if it is the same process in the SC in NZ as it is in Aus, and I mentioned that the distributor shouldn't be in the SC for the LVL that needs to fabrication. Though I spoke to someone from Manufacturer 1 and they mentioned that the distributor is sometimes needed in the chain because they typically supply a lot of materials to the distributors and then if smaller fabricators only require a small amount of LVL the manufacturer may just say get it from the distributor as they typically don't supply small amounts on a project basis.

J: That's interesting and fabricators mentioned the other thing over here. The communication between the manufacturer and the fabricator is not ideal at the moment and the manufacturer doesn't sometimes understand what the product before, and it was even suggested by fabricators that the manufacturer should actually put the packet together for a job knowing that the LVL is project based as opposed to going to a timber merchant. This should be done to minimise cutting at fabrication - the material going into the packet is NOT cupped. The manufacturer essentially has just been giving them whatever material is inventory and not having any regard for what its next use is. They don't really pay attention on what they actually send out.

M: That similar issue occurred for the floors used for testing at UTS. Where they came cupped and had to be flat stacked to try and minimise the cupping.

J: Because typically once they're cupped it's difficult to get them straight - similar issues over here where manufacturers are delivering material that is cupped and shouldn't have ever happened in the first place - the issue is also where it occurs in manufacturing and during transit.

M: I have received feedback that in Australia low quality plastic is used by some manufacturers during transit.

M: Do you think an integrated supply chain e.g. alliance, partnership, vertical integration has potential to address the current fragmentation current in the supply chain for prefabricated timber products.

J: Yes, I guess ahh, yeah I would support that where alliances, partnering, VI could help with a number of things including certainty in cost, delivery - really just more collaborating and partnering where everyone is aware of each others problems will help to produce better buildings.

M: I think a lot of that as well from the manufacturer - the end of the day their KPIs is just how much materials they get out the door - if they are meeting these m^3 targets their jobs are done in their ideas - I think they should have more interest in where their product is going.

J: Yes, they should have an interest that if they are doing a good job for their customers it will benefit them going forward.

Appendix D – Example of semi-structured interview questions R1 Australia/NZ

1. Are the manufacturing capabilities of EWP i.e. LVL, glulam in Australia and NZ limiting the feasibility of multi-storey timber buildings?

2. In Australia/NZ is the fabrication process an issue in the supply chain for large prefabricated timber systems? If so who do you see as having the greatest potential to address this in the future?

3. Is there adequate design expertise in the construction industry in Australia/NZ to design multi-storey timber buildings? If not how do you think this issue can be addressed?

4. Are building codes are an inhibitor to the uptake of take of timber in multi-storey construction in Australia/NZ? If so what do you think are the best ways to address current code limitations?

5. Which on-site trade do you see most likely to install timber members i.e EXPAN systems in multi-storey non-residential buildings?

6. What is the nature of the firm relationships along the supply chain for large prefabricated timber systems i.e. EXPAN?

7. What are the power relationships between firms and their suppliers along the chain for large prefabricated systems i.e. EXPAN??

8. Do you think an integrated supply chain i.e. alliances, partnering or vertical integration has the potential to address the current fragmentation present between companies in the Australian timber industry (multi-storey non-residential market)?

9. Overall what areas of the supply chain of multi-storey non-residential timber construction in Australia/NZ have the greatest risk to time, costs & quality on projects?

Appendix E – Example of semi-structured interview questions R2 Australia/NZ

Part 1 – Company background

Business model and size

1. How many offices do you have and where are they located?

2. Where are most of the projects you are involved in located?

3. How is the company structured and what levels exist? i.e. state, national, multi-national

4. What is the annual turnover for the business?

Products and services

5. Can you describe what your business does, i.e. product supply, services offered (design, fabrication, installation etc)

Markets and competitors

6. How many different types of products do you supply? What markets of the construction industry do you predominately supply to? i.e. residential, commercial, industrial etc.

7. How many direct competitors do you have in each market you supply to?

8. Who are your major competitors?

9. How does your product/service differ from your competitors? What do you compete on? i.e. price, service, product, reputation etc

Part 2 – Project Characteristics

1. What is the typical role of your firm on projects? i.e. supply product, level of service…

2. How often do you change/'customise' your level of service, to suit a clients' needs for a particular project?

3. How important is it being close to a project/client?

4. When are you typically engaged on projects? i.e. concept design, detailed design, tender (after design is complete)

5. Do you ever provide input during the design phase? If so how? i.e. fabrication issues of certain designs/details, cost/lead time issues for certain designs…

Part 3 – Client/supplier relationships

Clients

1. Who is typically your client on projects? i.e. who engages a contract with you

2. How do these arrangement come about? i.e. open tender, invited tender, long term relationship with client… What is the first thing that happens and then what happens next?

3. Why do you think you are typically chosen for projects? i.e. lowest price, service, past performance etc

4. How demanding are your clients, and are there high levels of communication whilst on projects?

5. Would you change anything about how you and your client work together? i.e. processes (communication), financial (progress payments)

6. Do you have any alliances/partnerships with your clients?

7. Do you ever deal with your clients' clients? i.e. if you deal with builder (head contractor typically) do you ever communicate with client i.e. developer/building owner

Suppliers

8. What organisations supply what to you?

9. In what ways are your suppliers similar or different?

10. How do you typically engage/approach suppliers? How many do you have to choose from?

11. What is the nature and degree of interaction/communication with suppliers? Do they provide technical advice with projects or do they merely supply commodity products?

12. What is the history between your organisations and your suppliers? Do you have long term partnerships with certain suppliers?

13. Do you have alliances/partnerships with certain suppliers? If so, what do these entail?

14. In what ways do you manage suppliers? i.e. low (none outside the contract), medium (hold meetings outside projects to discuss processes and products & match your processes to theirs) or high (align strategic planning and sharing future directions)

15. Do you ever deal with your suppliers' suppliers?

16. What would you change about the way you interact with your suppliers?

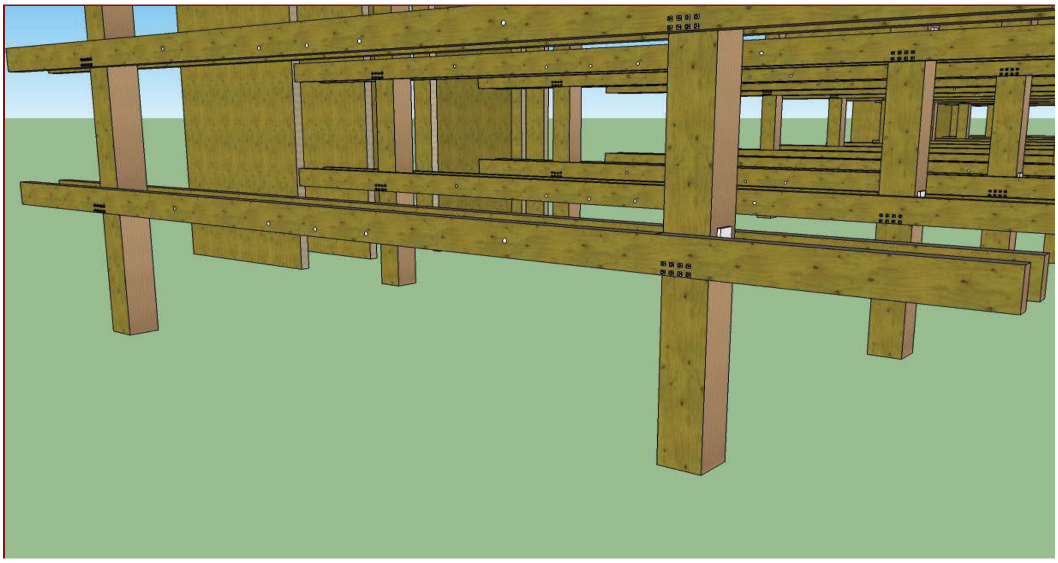
Appendix F – Virtual building case study used to test SBE model

The following designs are indicative only and should only be used as a guide regarding the possibilities of post-tensioned timber.

Gravity Frames

A total of 11 gravity frames (Figure A) are used with a distance of 8.4m between each frame. The max span between the frames is 14.4m, 7 Type 06 15.3mm diameter post tensioning tendons are placed at mid-span and stressed at an initial value of 57% of their yield stress – as mentioned earlier the post-tensioning cables won't be covered in this analysis.

Figure A Gravity beams

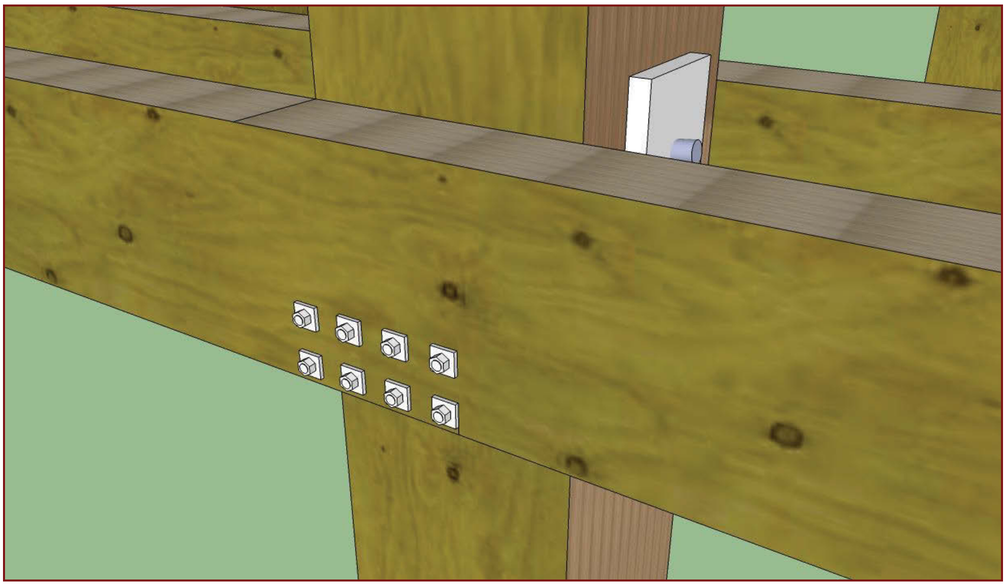


As shown above two continuous beams are used being 0.6m deep by 0.25m in width. The beams are bolted to two solid LVL columns 0.7m square. The tendons have a draped profile maintained by steel deviators to be glued into the beam sections. 5 deviators are used of 60mm in diameter.

Gravity Frame Connections

The connection between the two gravity beams and the column consists of 8 threaded rods of diameter 24mm to be used as bolts (Figure B). These bolts are placed at the bottom of the section to ensure they do not interfere with the draped tendon.

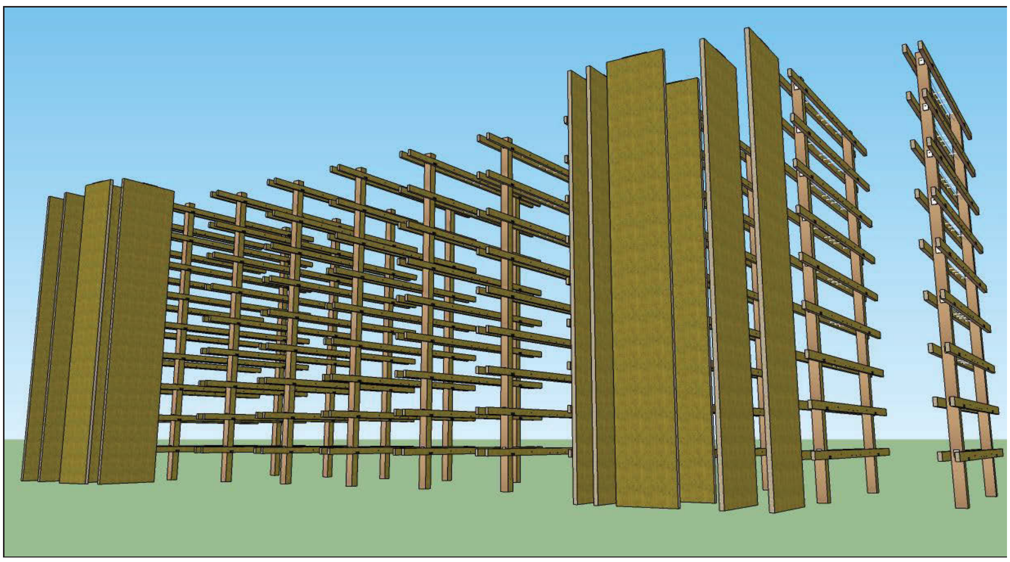
Figure B Bolted Connection to Gravity Column



Lateral Load Resisting Wall System

As mentioned the lateral load resisting system of the building is a series of core walls (Figure C) hat resist lateral loading in each direction. There are two groups of these walls each made up of 4 6m long walls in the long direction of the building and 2 4.2m walls in the shorter direction of the building.

Figure C Shear Wall Groups



Each walls has 4 groups of 7 Type 06 15.3mm diameter tendons with an initial stressing value of 70% of their yield stress. The tendons are placed inside a cavity in each wall and fixed against a thick steel plate at the end of each wall as shown in Figure D.

Figure D Shear wall end connections