FLEXIBILITY STRATEGIES FOR ENGINEER-TO-ORDER CONSTRUCTION SUPPLY CHAINS

by

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2011

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This thesis is dedicated to the memory of Mark Rogers, who sadly passed away in 2006.

ABSTRACT

Product proliferation as a result of meeting ever increasing customer demand preferences is well documented. In addition, customisation has been promoted as a source of competitive advantage. Despite these factors, most of the published research in operations and supply chain management has neglected the needs of the engineer-to-order (ETO) sector, where each product, or project, is designed for the needs of a specific customer. This thesis investigates definitions, models, concepts and strategies for the ETO supply chain structure. In particular, it ETO supply chains are researched within the specific context of the construction sector.

The high levels of uncertainty associated with such supply chains presents an array of challenges for organisations in the sector. This thesis focuses on methods to identify and categorize uncertainty, and the types of flexibility that can be developed to mitigate such uncertainties. The importance of good 'pipeline management' is also highlighted, which is an area that is lacking in the construction management literature.

Initially, the ETO supply chain is defined in relation to five other 'structures', which describe the flow and control mechanisms of products throughout different supply chains. A key defining characteristic is that the 'decoupling point' is located before the design stage. A structured literature review is then undertaken, which integrates construction supply chain research with wider ETO research. Construction and ETO bodies of knowledge have largely evolved in isolation, within different disciplines, academic communities and journals. This thesis integrates these bodies of knowledge.

A critical realist stance is adopted in the thesis, and a range of research methods are utilised within a multiple case design. The empirical research is structured in two phases. Firstly, case studies are undertaken in the construction industry. Three units of analysis are specified in the case research: network co-ordinators, projects and supplier pipelines. In total, the case investigation involves two 'network co-ordinators', five projects and twelve 'supplier pipelines', across two ETO construction systems. Secondly, six evaluation interviews are undertaken, using participants from a range of ETO construction industries.

Flexibility is identified as an important strategic capability for ETO supply chains, and a conceptual model for supply chain flexibility is developed and investigated. A four step route map, which brings together different elements of the thesis, is a key output from the research, and provides a practical guide for practitioners to follow when considering flexibility strategies. The overall findings suggest that by becoming more flexible ETO construction supply chains can mitigate some of the uncertainties experienced, but this requires due consideration of supply chain uncertainties, pipeline management, and the correct types of flexibilities vis-à-vis collaborative arrangements. A contribution is made to the fields of uncertainty and flexibility within the context of ETO construction.

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LIST OF ABBREVIATIONS

ABS: Association of Business Schools
ATO: Assemble-to-order
BTO: Build-to-order
BPR: Business Process Re-engineering
BSE: Business Systems Engineering
CAD: Computer Aided Design
CODP: Customer Order Decoupling Point
DTO: Design-to-order
ETO: Engineer-to-order
ETS: Engineer-to-stock
EPSRC: Engineering and Physical Sciences Research Council
GRP: Glass Reinforced Polyester
GDP: Gross Domestic Product
IGLC: International Group Lean Construction
IT: Information Technology
JIT: Just in Time
KPI: Key Performance Indicators
McCLOSM: Mass customised Collaborative Logistics for Sustainable Manufacture
MTS: Make-to-stock
RQ: Research Question
SME: Small Medium Enterprises
SMED: Single Minute Exchange of Dies
STS: Ship-to-stock
SWOT: Strengths Weaknesses Opportunities and Threats
TPS: Toyota Production System
UDSO: Understand, Document, Simplify Optimise
UK: United Kingdom
3D: Three dimensional

CHAPTER 1

INTRODUCTION

AIMS OF CHAPTER 1

1. **Establish the context and reasoning for the research in this thesis**
2. **Introduce the primary aim and research questions**
3. **Provide a summary of the literature gaps**
4. **Outline the structure of the thesis**

The turbulence of the modern business environment is well documented (Christopher, 2005). Globalisation, technological change and more demanding customers result in higher levels of uncertainty for organisations. Product proliferation as a result of meeting ever increasing customer demand preferences is well documented (Forza and Salvador, 2002). Customisation has been promoted as a source of competitive advantage (Amaro et al., 1999; Lampel and Mintzberg, 1996). Despite these factors, most of the published research in operations and supply chain management has neglected the needs of the 'engineer-to-order' (ETO) supply chain (Hicks et al., 2000).

The ETO supply chain can be defined in relation to a family of supply chain structures. Based on Hoekstra and Romme (1992) and Naylor et al. (1999) five different supply chain structures can be defined: buy-to-order, make-to-order, assemble-to-order, make-to-stock and ship-to-stock. These structures describe the flow and control structures of products throughout different supply chains. A 'decoupling point' can be used to distinguish the point at which the customer penetrates the supply chain (Naylor et al., 1999). A sixth supply chain structure, the ETO supply chain, is emerging as an addition to the five established structures, but it has received much less attention than the other structures (Hicks et al., 2001). However, at present there is no consensus on definitions, models and strategies that are suitable for this particular type of supply chain.

Uncertainty affecting supply chain operations has long been recognised by researchers as a major obstacle to the delivery of customer value in different supply chains (Childerhouse and Towill, 2004). Supply chain uncertainty can be defined as "situations in the supply chain in which the decision maker does not know definitely what to decide as he is indistinct about the objectives; lacks information about or understanding of the supply chain system or its environment; lacks information processing capabilities; is unable to accurately predict the impact of possible control actions on supply chain behaviour; or, lacks effective control actions" (van der Vorst and Beulens, 2002). Whilst it has been acknowledged that different types of supply chain have different uncertainty profiles, and that strategy must be matched with these profiles (Fisher, 1997; Lee, 2002), there is little academic literature addressing the particular uncertainties relating to the ETO supply chain, or how these uncertainties may be managed.

There have been numerous studies suggesting that a philosophy of 'one size fits all' strategy to supply chain management is not appropriate (Fisher, 1997). In particular, the application and suitability of different supply chain strategies, including the application of 'lean', 'leagile' and 'agile' approaches, have attracted much debate in academic literature (Christopher and Towill, 2000, 2002; Cooney, 2002; Cusumano, 1994; Hines et al., 2004; Katayama and Bennett, 1999; Naylor et al., 1999; Van-Hoek, 2000). Many authors agree that supply chains must be matched to specific markets, but there is less consensus relating to which strategies should be applied in which markets. The philosophy of 'one size does not fit all' has also been discussed in the area of project management (Shenhar, 2001) and logistics, where tailored logistics strategies are proposed (Bask, 2001; Fuller et al., 1993; Naim et al., 2006; Wang et al., 2007). However, it is unclear from this literature which strategies are appropriate for the ETO supply chain.

Agility has been proposed as an approach for dealing with the uncertainty found in modern globalised markets (Christopher, 2000). Agility, it is proposed, provides the capabilities required to keep up with the pace of change. It is no longer adequate to be low cost. Supply chains must be able to respond quickly to sudden changes in supply or demand, handle unexpected disruptions and reshape themselves in line with market requirements (Lee, 2004). They have to deliver exactly what the customer wants, in the right location, at precisely the right time. Flexibility is considered as an important enabler of this (Christopher, 2000; Naylor et al., 1999; Prater et al., 2001; Yusuf et al., 1999). The value of flexibility as a response to uncertainty is well documented (Gerwin, 1993; Schmenner and Tatikonda, 2005; Swamidass and Newell, 1987; Tang and Tomlin, 2008).

This thesis seeks to weave together the themes raised in this short introduction. An important theme is the need to achieve a tailored strategy for different supply chains, specifically those required for the ETO supply chain. It will support the development of definitions for the ETO supply chain structure and will investigate the problems associated with supply chain uncertainty. This will be undertaken within the context of developing agile, flexible supply chains. The initial research problems addressed in this thesis can be articulated as follows:

- Most of the published research in operations and supply chain management has neglected the needs of the ETO supply chain.
- There is no consensus on definitions, models and strategies that are suitable for the ETO supply chain.
- Whilst it has been acknowledged that different types of supply chains have different uncertainty profiles and that strategy must be matched with these profiles there is little academic literature addressing the particular uncertainties relating to the ETO supply chain, or investigation into how these uncertainties may be managed.

1.1 INDUSTRIAL AND RESEARCH CONTEXT

The ETO supply chain covers a range of industry sectors including construction projects, ship-building, aerospace, capital goods and high tech equipment, power plant, bespoke electronics and complex components in general manufacturing. As many areas of manufacturing are being outsourced to low cost locations such as China, these high value adding and complex supply chains form a vital part of the UK economy. The arena for the empirical work in this thesis is the construction industry. While the recession at the time of writing has led to a downturn in construction activity, the sector still accounts for approximately 8.5% of the UK GDP and employs around 3 million people across 300,000 firms (Cridland, 2010). The sector consumes huge quantities of materials, labour and other resources, and has been at the receiving end of a number of high profile Government reports seeking to drive improvements (Egan, 1998; Latham, 1994).

In this thesis, two supply chain networks form the construction industry are investigated in depth, covering a total of 5 projects and 12 suppliers. The first network focuses on the activities of a main contractor based in the South of the UK, which has a turnover of £70 million with a workforce of around 550 employees. Major clients include housing associations, care scheme operators, commercial and industrial concerns and schools. The organisation specialises in delivering projects on a design and build basis. It has won numerous awards for best developments, and has been included in a number of best practice guides written about client partnering and supply chain management. Three projects and nine suppliers are investigated from this network.

The second network investigated focuses on the activities of a global construction management company with a turnover of £530 million and 2800 employees. The organisation specialises in large commercial tower buildings delivered on a construction management contract basis. The company was voted in the top 5 of the Sunday Times 'top track' in 2008 and was also awarded the construction management organization of the year by a leading trade magazine. The organisation's approach to supply chain management and collaboration are well recognized in the industry. Two projects and three suppliers are investigated from this network.

The findings from these networks are then evaluated by interviewing employees from a range of construction sectors. These include house building, commercial buildings, civil engineering, as well as representing a range of organisation types including clients, manufacturers, network co-ordinators, design, logistics and organisational bodies.

Organisations from both these networks were partners on an EPSRC funded research project at Cardiff entitled McCLOSM (Mass customised Logistics for Sustainable Manufacturing). McCLOSM was a 5 year industry linked project examining frameworks for logistics and supply chain across the 3 sectors of steel, construction and retail, running between 2004 and 2009. This thesis draws on the construction related activities undertaken in the project, which the author was solely responsible for.

1.2 AIM AND RESEARCH QUESTIONS

The literature introduced in the initial section will be developed further in the literature review. There is clearly a need for more clarity in the ETO body of knowledge, especially with respect to definitions and strategies tailored specifically for the ETO supply chain. This thesis offers an empirical investigation into the uncertainties experienced in the ETO supply chain and the specific flexibility strategies required for mitigating these uncertainties. In doing so, definitions of the ETO supply chain, and of supply chain flexibility, are developed. During this research the author attended an executive supplier training day held by an ETO organisation. At this event the chief executive of the organisation began his address with the following

"You have got to be flexible – or you will be rolled over"

Bringing these themes together, **the primary aim of this thesis is to develop a framework for achieving appropriate flexibilities to mitigate the uncertainties in ETO construction supply chains.** This overall aim is reduced to 4 research questions. These are articulated in the following section and are developed more fully in the literature review chapter. Each of the research questions is related to a specific literature gap. A summary of the literature gap associated with each of the research questions and the primary aim can be found in table 1.1. This table is revisited in the final section to include conclusions to the research questions and specific contributions.

1. *Research question 1: How does construction fit within a taxonomy of supply chain structures?* This question addresses the underlying structure of construction supply chains. In the academic literature, construction and ETO supply chain bodies of knowledge have evolved in isolation and have not been integrated. This thesis considers construction supply chains within a range of proposed supply chain structures. In doing so, construction is placed within the ETO structure, where much of supply chain is customised for an individual customer order. This research question is addressed in chapter 2, but aspects of the case research are also used to

make final conclusions for this question. An answer for this question is articulated following the analysis of the evaluation interviews in chapter 8.

2. *Research question 2: How can the sources of project uncertainty in ETO construction supply chains be identified and categorised?* Uncertainty can lead to a range of negative consequence for supply chains. This research question considers how uncertainties can be identified and categorized in ETO construction supply chains. A five-stage method is developed, bringing together a range of concepts and techniques. This five-stage model is applied to five construction project to demonstrate how it may be applied to a group of projects. In doing so, the supply chain uncertainty circle is applied to ETO construction industries for the first time, and the interactions between the uncertainties in construction supply chains are investigated. This research question is explicitly addressed in chapter 5.

Summary of Literature Gap	Research Question
In the academic literature, construction and ETO supply chain bodies of knowledge have evolved in isolation and have not been integrated.	(1) How does construction fit within a taxonomy of supply chain structures?
The supply chain uncertainty circle has not been applied in ETO construction industries, and the interactions between the uncertainties have received little attention.	(2) How can the sources of project uncertainty in ETO construction supply chains be identified and categorised?
While the client-main contractor relationship has been well researched in the construction sector, the relationship between main contractors and subcontractors has not been well researched. Furthermore, pipeline research has focused primarily on high volume, stable supply chains.	(3) How can organisations improve pipelines in ETO construction supply chains?
Much of the research relating to flexibility has addressed non ETO manufacturing. There is a recognition that the scope needs to be widened to consider the flexibility of the whole supply chain, but the literature in this area is at a very early stage of development. Flexibility has not been investigated empirically in the ETO construction sector.	(4) How can flexibility be rationalised in ETO construction supply chains?
Primary Aim	
Bodies of knowledge on uncertainty, flexibility, pipelines and collaboration have largely evolved independently, and have not been integrated for the specific needs of the ETO construction sector	Develop a framework for achieving appropriate flexibilities to mitigate the uncertainties in ETO construction supply chains

Table 1.1: Summary of literature gaps and contribution associated with each research question

3. *Research question 3: How can organisations improve pipelines in ETO construction supply chains?* While the client-main contractor relationship has been well researched in the construction sector, the relationship between main contractors and subcontractors has not been well researched. Furthermore, pipeline research has focused primarily on high volume, stable supply chains. In the specific context of the ETO construction supply chain, this research question considers improvement strategies for the activities that take place in the 'pipeline': the activities that take place between an order being generated and the receipt of that order by the buying organisation. Through this question, lead times, problems in the pipeline and sources of competitive advantage are investigated. Recommendations for pipeline improvement are made. This research question is explicitly addressed in chapter 6.

4. *Research question 4: How can flexibility be rationalised in ETO construction supply chains?* Much of the research relating to flexibility has addressed non-ETO manufacturing. There is a recognition that the scope needs to be widened to consider the flexibility of the whole supply chain, but the literature in this area is at a very early stage of development. Flexibility has not been investigated empirically in the ETO construction sector. This research question addresses this gap, and prompts the development of a conceptual model for supply chain flexibility. This model is then investigated by considering flexibility types in two ETO construction networks. In particular, the role of supply chain flexibility in supplier selection is explored. This research question is explicitly addressed in chapter 7.

1.3 STRUCTURE OF THESIS

The structure of the thesis can be visually followed using the schematic in Figure 1.1. This diagram is positioned at the start of each chapter to act as a 'signpost'. It shows that chapters 2, 3 and 4 are theoretical and Chapters 5, 6 and 7 are primarily empirical. Chapter 8 provides a discussion of the findings with an empirical evaluation phase of the research. The findings of the different research phases are integrated. Chapter 9 draws conclusions from all phases of the research.

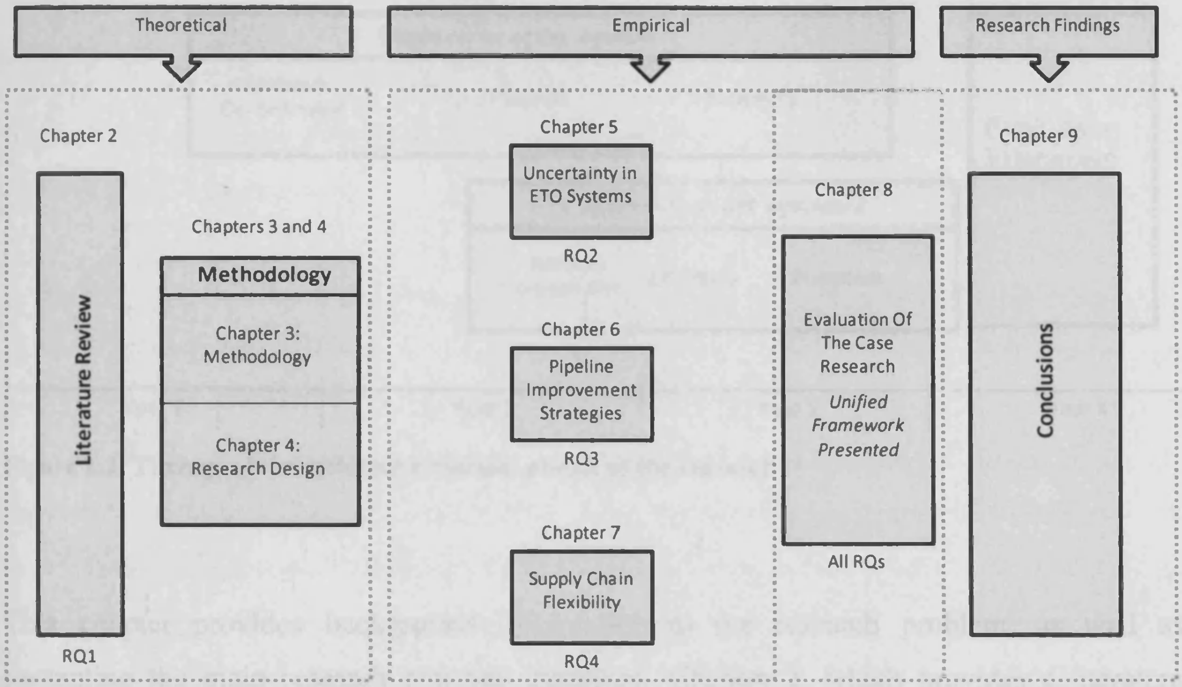


Figure 1.1: Thesis structure

The empirical phase of the research can be separated into two parts. As shown in figure 1.2, the first phase of the research process is an extensive case study research of two ETO 'systems'. The ETO systems are made up of three main units of analysis. These are a network co-ordinator, projects and supplier pipelines. These units of analysis are described in greater detail in the methodology chapter. In total, across the two systems, there are 2 network co-ordinators, 12 supplier pipelines and five projects. As shown in Figure 1.2, system 1 was investigated from year 1 to year 3 of the research process and system 2 was investigated over the course of years 2 and 3. The evaluation interviews were conducted at the beginning of year 4. Chapters 5-7 present the empirical findings from the case study phase of the research, using data collected from both ETO systems. Chapter 8 presents the empirical data gathered from evaluation interviews.

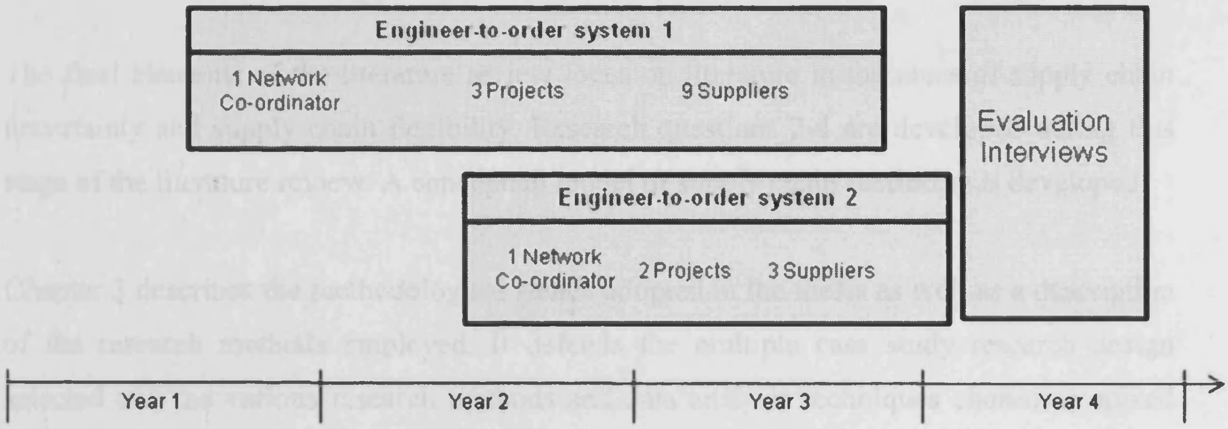


Figure 1.2: Timings of the different empirical phases of the research

This chapter provides background information to the research problem, as well as presenting the main research aim and questions. Chapter 2, which provides a literature review, traces the formulation of these research questions from the literature, showing the origins of the research questions. The initial part of the review, which examines the characteristics of different supply chain structures was first presented at the 'Construction management and economics: past, present and future' conference in 2007. The full reference is as follows:

Gosling, J. Naim, M. M. Fowler, N. and Fearne, A. (2007). "Defining the lean and agile characteristics of engineer-to-order construction projects". Construction Management and Economics: Past, Present and Future, Reading (CME25), Reading, UK.

Chapter 2 also offers a structured literature review for papers that are specifically related to the ETO supply chain. This part of the literature review also addresses research question 1 (How does construction fit within a taxonomy of supply chain structures?). This structured literature review has been accepted for publication in the *International Journal of Production Economics.* The full reference is:

Gosling, J. and Naim, M. M (2009). "Engineer-to-order supply chain management: A literature review and research agenda". International Journal of Production Economics, Vol. 122. Pp 741-754

The final elements of the literature review focus on literature in the areas of supply chain uncertainty and supply chain flexibility. Research questions 2-4 are developed during this stage of the literature review. A conceptual model of supply chain flexibility is developed.

Chapter 3 describes the methodological stance adopted in the thesis as well as a description of the research methods employed. It defends the multiple case study research design selected and the various research methods and data analysis techniques chosen. A mixed methodological approach is taken, using qualitative and quantitative techniques. While the study is primarily qualitative, quantitative data provides an important contribution to the thesis. The strengths and weaknesses of different methods are evaluated.

After chapter 4 the empirical part of the study begins. Chapter 5 answers research question 2 (How can the sources of project uncertainty in ETO construction supply chains be identified and categorised?), and is primarily concerned with the 'project' unit of analysis. The uncertainties experienced in 5 different ETO projects are identified and analysed. This work was first presented at the European Operations Management Association in Gothenburg, Sweden. The full reference for the paper is:

Gosling, J. and Naim, M. 2009. "Sources of project uncertainty in an engineer-to-order system" European Operations Management Association (EurOMA) Gothenburg, Sweden: 14th-17th June.

Chapter 6 is concerned with describing and analysing 'pipeline' activities across the 12 different supplier pipelines case studies used in the research. The chapter answers research question 3 (How can organisations improve pipelines in ETO construction supply chains?), and is primarily concerned with the 'supplier pipeline' unit of analysis. The generic activities in the pipeline are described and the results of a 'pipeline survey' are analysed. Some of the early ideas for this chapter can be found in a paper published in the *International Journal of Agile Manufacturing*. The full reference is:

Gosling, J. Naim, M. Fowler, N. and Fearne, A., 2007. "Manufacturers' preparedness for agile construction". International Journal of Agile Manufacturing, 10(2), 113-124.

While chapter 7 is primarily concerned with the network co-ordinator unit of analysis it examines the functioning of the whole ETO system. The conceptual model of supply chain flexibility is explored in this section, which answers research question 4 (How can flexibility be rationalised in ETO construction supply chains?). This chapter is largely based on a paper that has been published in the *International Journal of Production Economics.* The full reference is:

Gosling, J. Purvis, L. and Naim, M. M., "Supply chain flexibility as a determinant of supplier selection". International Journal of Production Economics, Vol 128, Issue 1, pp 11-2.

Chapter 8 assesses the main learning points from the case study research and explores the implications for industry. It includes empirical data using feedback from professionals in a range of ETO organisations. This chapter offers an indication of the potential to generalise the findings to different ETO construction environments. The empirical data is used to evaluate the findings and the implications of the case study research across different ETO construction sectors, and for different members of the supply chain. The findings for each of the research questions are discussed in the light of the evaluation interviews. An answer for research question 1 (How does construction fit within a taxonomy of supply chain structures?) is formulated for the first time in the thesis. A framework for achieving supply chain flexibility is articulated at the end of this chapter, bringing together all the different elements of the study.

Finally, chapter 9 presents the conclusions. The overall research findings are summarised, and the original research contributions are discussed. The chapter finishes by discussing both the academic and the practical implications of the findings along with limitations and the potential for future research.

1.4 SUMMARY

This chapter has outlined the context for the thesis and has introduced the primary aim. It provides an overview of the thesis as a whole. A broad background to the ETO supply chain has been presented and the key areas of literature have been introduced. To support the primary aim of the thesis, 4 research questions have been articulated. These will be developed more fully in the next chapter. A summary of the structure and the different phases of the empirical research have been introduced. The next chapter will provide a more fully developed contextual background for the thesis through the literature review, which identifies gaps and shortfalls in the literature.

SUMMARY OF CHAPTER 1 AIMS

1. **Establish the context and reasoning for the research in this thesis**
   - The context and motivation for research on ETO supply chains has been introduced
2. **Introduce the primary aim and research questions**
   - The primary aim is to develop a framework for achieving appropriate flexibilities to mitigate the uncertainties in ETO supply chains.
   - Four research questions and four research propositions have been introduced
3. **Provide a summary of the literature gaps**
   - A summary of the literature gaps and research questions can be found in table 1.1
4. **Outline the structure of the thesis**
   - A summary of the structure and the different phases of the empirical research has been presented

CHAPTER 2

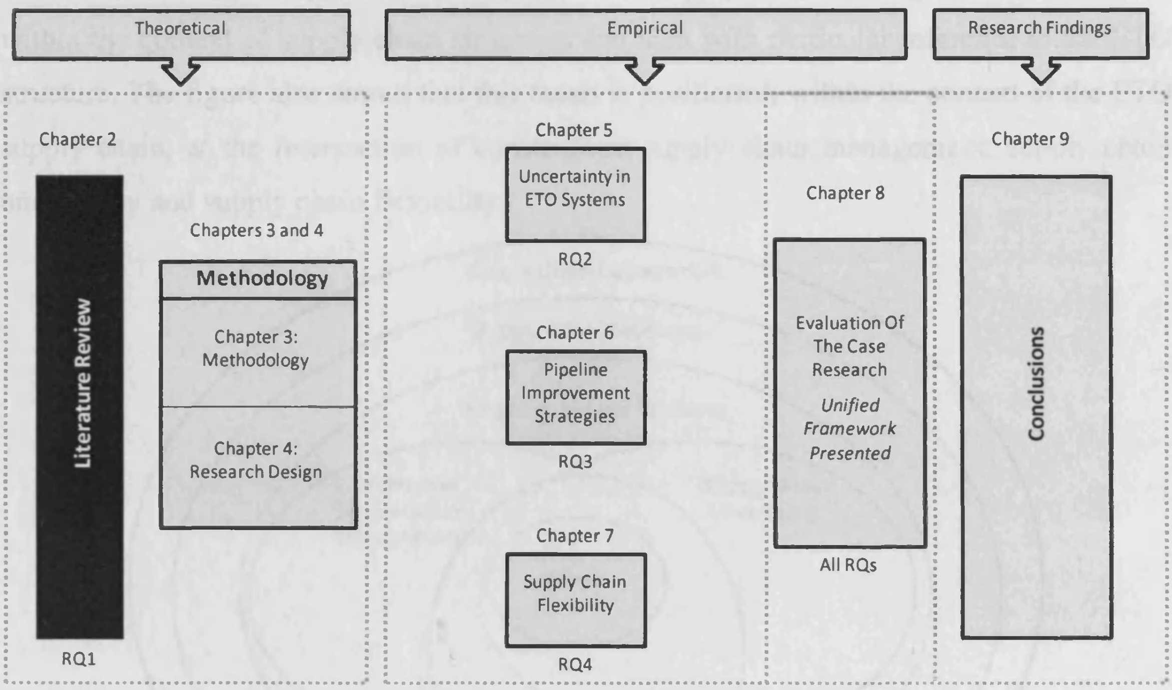
LITERATURE REVIEW

CHAPTER 2 AIMS

1. Develop a foundation for the thesis in the published literature
2. Formulate research questions in relation to the literature and identify the research gaps
3. Identify the characteristics of the engineer-to-order supply chain
4. Compare the engineer-to-order supply chain with other types of supply chains
5. Develop a conceptual model to rationalise supply chain flexibility

RESEARCH QUESTION ADDRESSED

RQ1: How do construction supply chains fit within a taxonomy of supply chain structures?



2. INTRODUCTION

This chapter establishes the theoretical foundations of the thesis. It provides an overview of the published literature that is related to the main research areas and highlights relationships between these different bodies of knowledge, showing how different areas interact. The principle subject areas of the thesis are articulated and research questions are formulated. The review will also highlight gaps in the literature.

The areas of academic research and their relationships are summarised in the Venn diagram in figure 2.1. The broadest area of literature is the field of supply chain management. Within the field of supply chain management the literature relating to supply chain structures can be placed. One specific structure from a range of supply chain structures is then addressed: the ETO supply chain. The figure shows that there are two more bodies of knowledge that cut across those already described. Construction supply chain management is discussed within the context of supply chain structures and then with particular reference to the ETO structure. The figure also shows that this thesis is positioned, within the context of the ETO supply chain, at the intersection of construction supply chain management, supply chain uncertainty and supply chain flexibility.

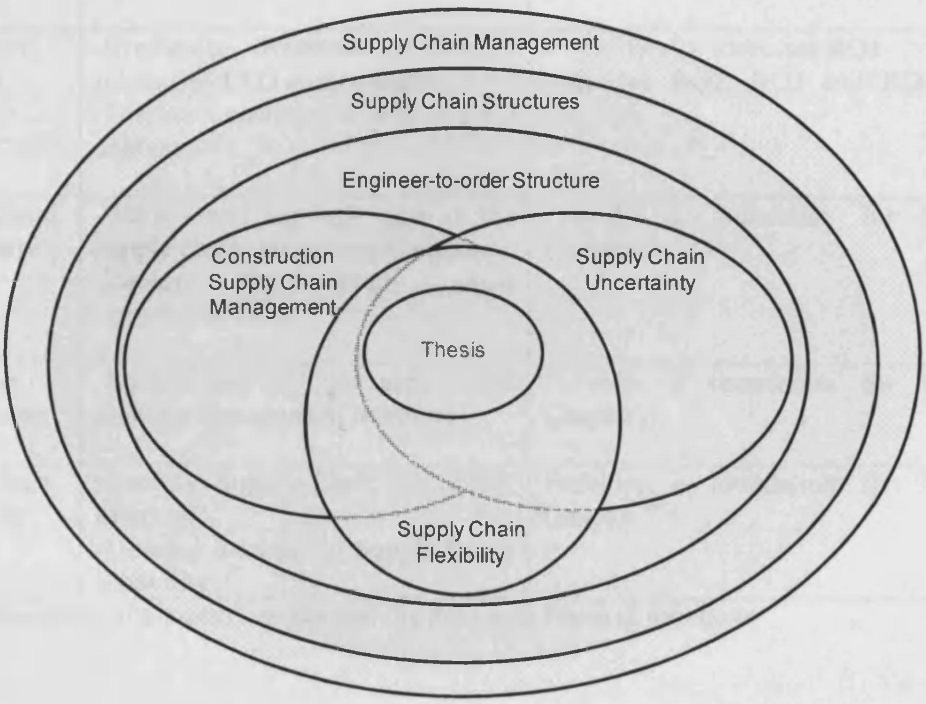


Figure 2.1: Venn diagram to show interaction between bodies of knowledge

This review begins with a general grounding in supply chain management including definitions, and then moves on to review literature relating to supply chain management in the construction industry. Literature relating to supply chain structures is reviewed and a taxonomy of structures is developed. A structured literature review specifically relating to the ETO supply chain structure is then offered. This is an important section of the literature review as it addresses research question 1 (How does construction fit within a taxonomy of supply chain structures?). The final sections then review the literature related to uncertainty and flexibility, two of the major themes in this thesis. This area of the review develops a model for supply chain flexibility which is investigated empirically later in the thesis. Table 2.1 shows the aims of each part of the literature review, the relevant bodies of knowledge, and the link with research questions.

Bodies of Knowledge	**Aims**	**Link with Thesis and Research Questions**
Supply Chain Management	Locate thesis within the supply chain management discipline	-Facilitates overall positioning of thesis -Provides theoretical grounding for all research questions and chapters
Construction Supply Chain Management	Provide an industrial context for the research	-Industrial context for all research questions and chapters
Supply Chain Structures	Develop a taxonomy of supply chain structures and identify their characteristics	-Facilitates overall positioning of thesis -Provides theoretical grounding for all research questions and chapters
ETO supply chain	-Synthesize literature specifically relating to ETO supply chains -Discuss construction within ETO context	- Specifically addresses RQ1 - Guides RQ2, RQ3 and RQ4 and all chapters
Supply Chain Uncertainty	-Review and highlight gaps in the supply chain uncertainty literature -Review the supply chain uncertainty circle	Provides a foundation for RQ2 and Chapter 5
Pipeline Manageemnt	-Review and highlight gaps in the pipeline management literature	Provides a foundation for RQ3 and Chapter 6
Supply Chain Flexibility	-Classify Supply Chain Flexibility Literature. -Develop a model of Supply Chain flexibility	Provides a foundation for RQ4 and Chapter 7

Table 2.1: Summary of literature review and the links with research questions

2.1 SUPPLY CHAINS AND SUPPLY CHAIN MANAGEMENT

It has been argued that in the modern business environment supply chains compete, not individual companies or organisations (Christopher, 2005). Firms can no longer compete effectively in isolation of from various members of the supply chain. The field of supply chain management appears to have originated in the early 1980s and has since rapidly expanded (Harland, 1996). However, it remains fragmented and the emerging bodies of knowledge or 'functional silos' within the field remain largely unconnected (Burgess et al., 2006; Harland, 1996). A distinction is made between supply chains as phenomena that exist, and the management of those supply chains (Mentzer et al., 2001). The rest of this section explores the definitions of 'supply chain' and then 'supply chain management'.

Harland (1996) proposes a useful framework to illustrate the different levels of research and conceptual development within supply chain management. The different levels proposed are:

1) The internal chain. This refers to the internal flow of materials and information within one specific company;
2) Dyadic relationships. This refers to the company and its immediate supplier or customer;
3) The external chain. This refers to the dyad and the extended supply chain including the supplier's supplier and the customer's customer;
4) The network. This refers to the complete network of organisations involved in the provision of a product or service required by an end customer.

Different chapters in this thesis address different levels of research. The units of analysis in this thesis are discussed in depth in the Methodology chapter.

It is also important to note the use of the term 'value chain' and 'value stream' within supply chain management. Value chains and value streams have been espoused by a number authors, most notably by Womack and Jones (1996) and Porter (1985). This provides an approach for thinking about the value to the customer offered by different activities not only in an individual organisation but across a supply chain. Supply chains, it is argued, are made up of one or more value chains (Childerhouse and Towill, 2003).

2.1.1 Definitions of a supply chain

Mentzer et al. (2001) suggest that the definition of 'supply chain' is more common across authors than the definition of 'supply chain management'. There is an abundance of definitions for a supply chain including:

- "A system whose constituent parts include suppliers of materials, production facilities, distribution services and customers, all linked together via the feed forward flow of materials and the feedback flow of information" (Stevens, 1989);
- "The network of connected and interdependent organisations mutually and co-operatively working together to control, manage and improve the flow of materials and information from suppliers to end users" (Christopher, 2005);
- "The functions within and outside a company that enable the value chain to make products and provide services to the customer" (Cox and Blackstone, 1998);
- "All those activities associated with moving goods from the raw materials stage through to the end user. This includes sourcing and procurement, production scheduling, order processing, inventory management, transportation, warehousing and customer service. It also involves the information systems necessary to monitor these activities" (Quinn, 1997);
- "All activities associated with the flow and transformation of goods from raw materials stage, through to the end user, as well as the associated information flow. Materials and information flow up and down the supply chain" (Handfield and Nichols, 1999).

For the purposes of this thesis, a supply chain will be defined as "a system whose constituent parts include suppliers of materials, production facilities, distribution services, resources and customers, all linked together via the feed forward flow of materials and the feedback flow of information" (adapted from Stephens, 1989). This definition captures the 'systems' perspective adopted in this thesis. A system may be described as recognizable whole which consists of a number of parts that are connected up in an organised way. This recognizable whole includes a boundary, an environment, a purpose and emergent properties (Waring, 1996). A systems philosophy demands that an uncoordinated approach is replaced by a framework in which the identities of the separate parts are subsumed by the identity of the total system. Via a system engineering approach, the individual elements and subsystems are designed and fitted together to achieve an overall system purpose, where the right parts must be connected and in balance if the system is to produce the desired results (Parnaby, 1995; Towill, 1997b). The Stevens (1989) definition has been adapted to make it more relevant to the ETO supply chain. It includes resources, such as labour and working capital, which are required to flow through ETO supply chains to fulfil individual project requirements.

2.1.2 Definitions of Supply Chain Management

There appears to be little consensus on the definition of supply chain management (Lummus and Vokurka, 1999; Mentzer et al., 2001; New, 1997). This is reiterated by Croom et al. (2000) who argued that there is a confusing profusion of overlapping terminology and meanings in supply chain management. The following definitions show some of the perspectives on supply chain management:

- "An integrative approach to dealing with the planning and control of the material flow from suppliers to end users" (Ellram, 1991);
- "An integrative philosophy to manage the total flow of a distribution channel from supplier to ultimate user" (Cooper et al., 1997);
- "The systematic, 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 individual companies and the supply chain as a whole" (Mentzer et al., 2001);
- "The management of 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, 2005);
- "The management, control and coordination of material, cash, resource and information flows in order to construct habitable dwellings based on specific design

requirements, including the appraisal and selection of skilled labour and material suppliers" (Childerhouse et al., 2000).

For the purposes of this thesis, supply chain management will be defined as "the management, control and coordination of material, cash, resource and information flows in order to complete projects based on specific design requirements, including the appraisal and selection of suppliers" (Adapted from Childerhouse et al., 2000) . This definition is adopted for a number of reasons. Firstly, it captures the specific design requirements for projects that are an important part of the ETO supply chain. Secondly, it emphasizes the appraisal and selection of suppliers in supply chain management. This emphasis is important, as this thesis considers how network co-ordinators in ETO systems can achieve supply chain flexibility through robust sourcing and selection criteria for their suppliers.

2.1.3 Construction Supply Chains

As the empirical investigation is conducted with companies operating in the construction industry, this section will provide a description of the sector. Many authors believe construction is separate from all other industries because of its heterogeneous nature. Schonberger (1990) argued that "One industry, construction, is so fouled up as to be in a class by itself; delay, lack of coordination, and mishaps are normal, everyday events for the average company". As mentioned in the introduction, the UK Government has commissioned several reports to advise on improving construction including those of Egan (1998) and Latham (1994). The former make specific recommendations to the construction sector as a whole, in the areas of partnering the supply chain, lean construction and design standardisation.

A recent handbook on construction supply chain management (O'Brian et al., 2009) acknowledges that while the construction industry has recognized the importance of supply chain management to improve the performance of projects, initial research has shown how complex and ineffective they are in practice, and how immature the area is when compared to supply chain management in the manufacturing sector. An introduction to a special issue on supply chain management in the construction industry (Segerstedt and Olofsson, 2010) highlights the peculiarities of construction supply chains, such as one-of-a-kind products, temporary organization and site production, and questions the extent to which supply chain solutions from other industries are applicable.

Partnerships

One area that has been the subject of research in construction supply chains is that of partnering. Many authors, including the aforementioned UK Government initiatives, support the adoption of partnering within construction supply chains. Agapiou et al. (1998b) argued that the construction sector can best benefit from builders merchants by recognizing the importance of long-terms relationships and effective supply chain management. Fortune and Setiawan (2005) investigated the use of partnering practices by Housing Associations in the UK, and find that are a range of benefits to be gained by the use of partnering arrangements between clients and principal contracting organisations.

The uptake of supply chain management practices within construction, however, appears to be slow. In a survey of UK contractors by Akintoye (2000), it was concluded that the construction industry is still at its infancy with regard to adopting collaboration and supply chain management principles. Culture and management commitment are identified as key barriers, and the findings reveal that contractors are more oriented towards client partnering arrangements than with suppliers and subcontractors. These findings are supported by Saad et al. (2002), who found that although construction practitioners have some knowledge of supply chain management they need a better conceptual understanding of it, and new and more systematic approaches to its implementation. Barker and Naim (2008) also provided a survey examining a range of recognized indicators of supply chain sophistication in the housebuilding industry and find that awareness within the housebuilding industry was still low and that much inefficiency remains.

A number of authors have suggested that the partnership literature for construction supply chains has placed too much emphasis on client relationships, as opposed to those that might arise upstream. Proverbs and Holt (2000) developed a cost minimisation model for construction supply chains and suggest that although downstream alliances are common (contractor to client), there is a lack of upstream alliances (contractors and suppliers), which would increase the effectiveness of the whole supply chain. In particular, little attention has been paid to the integration of small and medium-size enterprises (SMEs) in the subcontractor and material supply sectors (Dainty et al., 2001a). A further study highlights serious concerns among subcontractors and material suppliers that point towards a fundamental mistrust and scepticism within existing supply chain relationships (Dainty et al., 2001b). Some authors question the extent to which full supply chain integration through partnering can be achieved in construction supply chains (Ireland, 2004).

Learning from Manufacturing and Lean Construction

A further theme within the construction supply chain management literature is the identification of the potential lessons that can be learnt from manufacturing research. Gann (1996) described the benefits to be gained from considering construction as a manufacturing process. In particular, the role of learning from the automotive industry is highlighted, whereby standardised parts are balanced with flexible assembly. The role of modularity in construction supply chains was investigated by Voordijk (2006), who used a 3 dimensional concept to describe product, process and supply chain modularity in the building industry.

Lean construction has also been promoted as a way of improving construction. Ballard and Howell (2002) introduced Lean Project Management, which is derived from Just-in-Time (JIT) principles. The same authors also promoted the shielding of production from uncertainty as a way of removing waste (Ballard and Howell, 1998), and the 'last planner' principle has also been proposed (Ballard and Howell, 2002). In the last planner system, the final person in the planning hierarchy to choose to carry out work that will be most productive is proposed in order to enable a more reliable work flow. Barker and Naim (2004) investigated the meaning of value and waste in house-building supply chains, and concluded that improvements can be facilitated by engineering change models. Naim and Barlow (2003) explored potential applications of lean and agile approaches in the construction sector from a supply chain perspective. The paper concluded that house-building supply chains have to be engineered according to whether the market objectives are low cost, flexibility or a combination of the two

Project Management and Construction

The literature on project management as applied to the construction sector is also pertinent for this thesis. As will be described throughout this literature review, the project nature of construction, and other ETO environments, presents inherent problems relative to more stable production environments. Winch and Carr (2001) focused on the role of process protocols to understand 'the shape' of the construction process. They identify generic stages of construction projects as define need, establish viability, conception, scheme design, detailed design, production planning, main trades, finishing trades, commissioning and facility management (Winch and Carr, 2001). These stages are used in chapter 4 to develop the research design adopted in the thesis.

The purpose of project management can be described as the challenge "to foresee or predict as many of the dangers and problems as possible and to plan, organize and control activities so that the project is completed as successfully as possible in spite of all the risks" (Lock, 2000). A wide range of books have been written on the subject of project management, from an operations management perspective (Maylor, 1999; Meredith and Mantel, 2003), and from a construction perspective (Clough et al., 2000; Winch, 2002). Lock (2000) provided a useful classification of four ETO project types:

1. Civil Engineering, construction, petrochemical, mining and quarrying projects – where the common feature is that the fulfilment phase must be conducted on a site that is exposed to the elements
2. Manufacturing projects – where fulfilment is conducted in a factory
3. Management Projects – where the end result is not principally an item of hardware or construction
4. Research projects – where the end objectives are usually difficult or impossible to define.

The focus of this thesis is category 1.

The classification above highlights the importance of on-site operations in construction supply chains. Vrijhoef and Koskela (2000) defined four roles for supply chain management in construction including a focus on the interface between the supply chain and the construction site, focus on the supply chain, focus on transferring activities from the construction site to the supply chain and focus on the integrated management of the supply chain and the construction site. They concluded that many of the problems in construction are caused by 'myopic control of the supply chain'. This highlights the debate relating to the extent to which construction activities should be completed offsite, in a factory controlled environment, or on-site (Segerstedt and Olofsson, 2010). Pheng and Hui (1999) investigated seven different ways in which JIT can be applied to site organization and layout, but concluded that JIT research in construction is in its infancy and requires more empirical testing.

From the review of literature relating to construction supply chains, the following can be concluded:

- Supply chain management is still in its infancy within the construction industry. The literature has focused on the client-contractor relationship rather than relationships with upstream material suppliers.
- Construction supply chains have a project and site elements which must be factored into any supply chain strategy. Learning from manufacturing has been identified as a theme within the literature, but it is unclear which approaches are most effective for the construction industry.

At this point, the first research question is posed:

Research Question 1: How does construction fit within a taxonomy of supply chain structures?

2.2 A TAXONOMY OF SUPPLY CHAIN STRUCTURES

This section will highlight differences between supply chain types, thereby highlighting the difficulties of managing ETO supply chains in comparison with those that are more stable. A range of supply chain structures have been proposed to illustrate the diverse range of supply chain operations. Based on Hoekstra and Romme (1992), Naylor et al. (1999), Yang and Burns (2003), Olhagar (2003) and Lampel and Mintzberg (1996) six different supply chain structures can be defined: engineer-to-order (ETO), buy-to-order (BTO), make-to-order (MTO), assemble-to-order (ATO), make-to-stock (MTS) and ship-to-stock (STS). Based on the aforementioned authors, figure 2.2 shows the level of standardisation and customisation that takes place before a customer order is received in each of the different supply chain structures. The shaded cells indicate that the activity is customised and the cells that are not shaded indicate a standardised activity. The line that runs through the different structures is the decoupling point, and shows the point at which the customer order enters the supply chain. The customer, in this case, is taken to be the next direct receiver of the material in the supply chain as opposed to the ultimate end user.

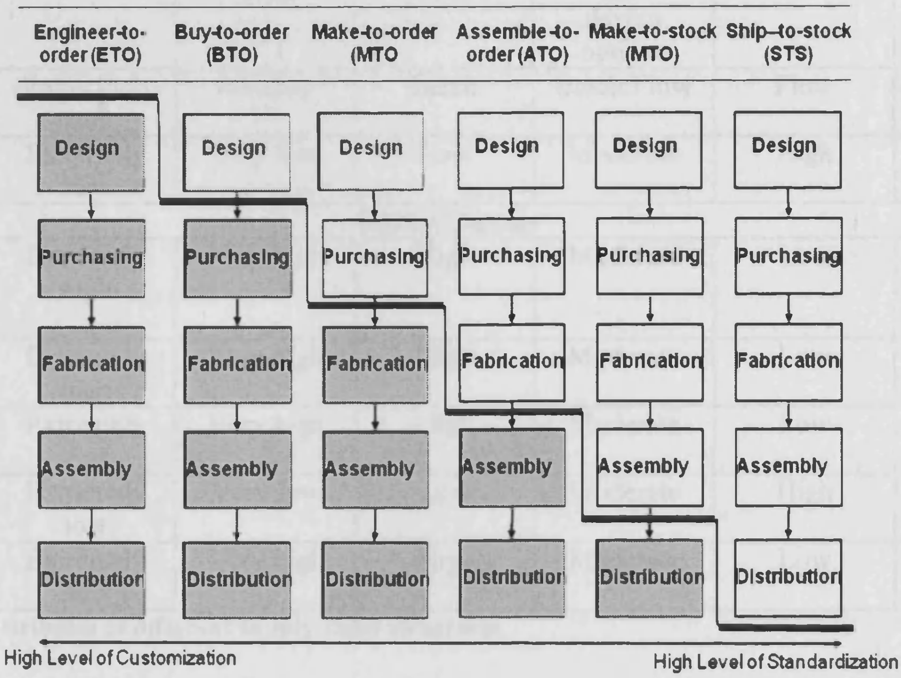


Figure 2.2: The six supply chain structures (Source: synthesis from various)

Differences between supply chain structures are identified through a synthesis of relevant literature review to create a number of dimensions that can be used to differentiate between the different structures. Table 2.2 summarises the main differences between the supply chain structures and the market outputs that each structure offers. The following section highlights some of the main differences by reference to the extremes of the spectrum and to intermediate structures as appropriate.

Attributes	**Engineer to order (ETO)**	**Buy to order (BTO)**	**Make to order (MTO)**	**Assemble to order (ATO)**	**Make to stock (MTS)**	**Ship to stock (STS)**
Decoupling Point	Design	Purchasing	Fabrication	Assembly	Distribution – Central	Distribution - Local
Purchasing	Identify sources of supply	Schedule product deliveries from suppliers	Hold raw materials / components	Fabricate or buy modules	Hold finished goods centrally	Hold finished goods locally
Stocks	No stock	No stock	Raw materials	Pre assembled modules	Finished goods	Finished goods
Design	Produce new design	Modify existing design	Pick from wide range of options	Pick from limited range of design options	Take design as is	Take design as is
Method	Project/job shop	Job shop	Batch	Batch/Flow	Flow	Flow
Forecasting Accuracy	Extremely low	Very low	Low	Moderate	High	Very High
Market Outputs						
Level of Customis-ation	Extremely high	Very high	High	Moderate	Low	Very Low
Variety	Extremely high	Very high	High	Moderate	Low	Very Low
Variability	Extremely high	Very high	High	Moderate	Low	Very Low
Volume	Extremely low	Very low	Low	Moderate	High	Very High
Time to Market	Extremely high	Very high	High	Moderate	Low	Very Low

Table 2.2: Attributes of different supply chain structures

2.2.1 Attributes of Different Supply Chain Structures

The Decoupling Point

The customer order decoupling point (CODP) is a stock holding point that separates the part of the supply chain that responds directly to the customer from the part of the supply chain that uses forecast planning. The decoupling point can act as a strategic buffer against the variability in demand and an efficient way of scheduling standardised parts. Upstream from the CODP all products are produced to forecast, whereas downstream from the CODP all products are pulled by the end-user (Christopher, 2000; Hoekstra and Romme, 1992; Mason-Jones et al., 2000; Naylor et al., 1999; Olhager, 2003). The decoupling point in the ETO supply chain lies at the design stage. The customer order asserts a high level of customisation for all activities in the supply chain. The decoupling point in the STS structure is the local distribution channel, hence there is no customisation whatsoever.

Purchasing and Stocks

The position of the decoupling point, described above, has a significant impact on the purchasing and strategic stockholding. Suppliers in an ETO structure are identified and mobilised in response to a specific customer order and would, typically, service a particular project. An ETO product may put every order out to competitive tender to a group of potential suppliers with the required capabilities (Amaro et al., 1999; Hicks et al., 2000). Stock will then be purchased according to the needs of a specific project. In a BTO structure the supply chain is established but no stocks are purchased. Product deliveries are scheduled from established suppliers after an order has been received. At the other end of the spectrum, the STS structure holds finished goods from established suppliers at a local distribution channel in order to satisfy forecasted demand very quickly.

Design

The level of influence that a customer has in the design process has significant implications for the supply chain. Based on Amora et al. (1999), the degree of design customisation can be categorized along five different classifications: produce new design, modify an existing design, pick from a wide range of design options, pick from a limited range of design options and take existing design as is. An ETO project will require a new design with a large amount of customer input, whereas an MTS or STS supply chain, for example, designs for a general market based on recommendations by marketing departments (Rahman et al., 2003a, b). Designs will show increasing levels of standardisation and reduced direct customer input the further the supply chain moves away from the ETO structure. In a BTO supply chain similar existing designs are modified to new customer requirements whereas the MTO and ATO mass customisation strategies are used to offer degrees of standardised options.

Production Method

The production method refers to the technique used to manufacture or assemble a product. Four popular assembly methods are job shops, batching, flow and project. The technique used will vary depending on the complexity and volume of the product (Ballard and Howell, 1998; Hicks et al., 2000; Porter et al., 1999). The production method for an ETO supply chain will closely resemble a project or job shop assembly method. Project production offers a unique product, requiring large scale inputs to be co-ordinated in order to achieve customers' requirements. An STS structure is more likely to involve flow production. Flow production is characterised by the large volume production of a small range of standard products (Porter et al., 1999). An ATO structure may involve a mixture of batch and flow production, with flow being utilised upstream from the CODP and batch utilised downstream from the decoupling point.

Forecasting Accuracy

The ease with which demand for a product can be forecasted has also been widely used to classify different supply chains (Fisher, 1997; Naylor et al., 1999; Olhager, 2003). The level of forecasting is closely related to demand volatility and the level of customisation. In supply chains where demand volatility and customisation is high the potential for forecast error usually increases. Supply chains that have more stable demand characteristics and standardised products can usually forecast demand more accurately. The level of forecasting possible in an ETO supply chain structure is extremely low in relation to other structures. The high degree of customisation and low volumes involved result in high levels of uncertainty and lumpy demand patterns. Any stock runs the risk of becoming obsolete and incorrect to specification. When products are more standardised and volumes are higher, such as in the MTS and STS structures, the level of forecasting possible increases, as it is possible to forecast aggregate demand more accurately. ETO companies often have to forecast skills, capacities and industry trends, whereas MTS companies are required to forecast the type of product, quantity and location (Rahman et al., 2003b).

Level of Customisation

Offering customisation to the market is increasingly becoming recognised as a source of strategic advantage (Lampel and Mintzberg, 1996; Pine, 1993; Salvador et al., 2007). This recognition of the strategic importance of satisfying true customer demand has been reflected in the supply chain literature, where market driven supply chains have received much attention (Childerhouse et al., 2002). The ability to fully customise according to the needs of an individual customer is a central feature of the ETO supply chain (Amaro et al., 1999). In other supply chain structures the levels of customisation offered to the customer are lower. For example in the ATO structure customisation is delivered in the form of standardized options or configure-to-order 'modules' (Naylor et al., 1999). In an STS supply chain the customer would have to take a standard product 'off the shelf'.

Production Volume

Product mix and volume have long been key classifications for production and supply chain operations (Olhager, 2003; Salvador et al., 2007). High and low volume supply chains pose different challenges to operations. When compared with high volume supply chains, low volumes often pose problems in terms of power regimes and uncertainty in the volumes of components required (Hicks et al., 2000, 2001). ETO products are generally characterised as high variety and extremely low volume, possibly 'one off' builds, whereas MTS products are often produced in large volumes (Cameron and Braiden, 2004).

Matching Production and Time to Market

The time to market for a product has also been used to categorise supply chains and manufacturing operations (Fisher, 1997; Olhager, 2003). The production to delivery time ratio (P/D Ratio) is often quoted as a method to make decisions about time to market. If the production lead time is greater than the desired maximum customer delivery time than that which is acceptable to the customer (P/D ratio is greater than 1) then a produce to stock, that is, either MTS or STS structure is more appropriate. If the production lead time is lower than the desired maximum customer delivery time than that which is acceptable to the customer (P/D ratio is lower than 1) then a supply chain does not necessarily need to produce to stock (Olhager, 2003). In an ETO structure, a customer is often exposed to the total supply chain, so the time to market can be extremely high. However, it is likely that the customer will be prepared to wait longer for a fully customised product and may agree to a due date at a negotiated cost at the design stage (Amaro et al., 1999).

This section highlights the inherent difficulties related to the ETO supply chain relative to more stable production environments. These difficulties can be summarised as follows:

- High variety – low volume environment;
- The customer is involved in the design process and hence there is more uncertainty relating to customization;
- The customer is exposed to all activities in the supply chain;
- The supply chain must be configured to account for the changing requirements of different projects.

2.3 THE ENGINEER-TO-ORDER SUPPLY CHAIN STRUCTURE

The aim of this section of the literature review is to provide a framework to understand the developments that have emerged in the literature relating specifically to the ETO supply chain, as well as providing a theoretical grounding for this thesis. More specifically, the objectives of this section of the literature review are:

1. Develop a more robust definition of the ETO supply chain;
2. Categorise the operational strategies that have been researched in the sector;
3. Investigate the relationships between lean and agile paradigms and the ETO supply chain;
4. Highlight the research methods and industry sectors that are prevalent or missing;
5. Explore the linkages and contributions to the development of the ETO supply chain from three different streams of knowledge: supply chain structures, ETO strategy and lean and agile literature streams;
6. Indicate directions for future research to develop the ETO supply chain.

Section 2.6 will address definitions of ETO supply chains, exploring the ETO supply chain in comparison to other supply chain structures and the different segments within the ETO type. The structured literature review is organised based on a classification of 3 'streams' of literature. Stream 1 relates to the body of knowledge pertaining to supply chain structures. This stream emerged from part 1 of the literature review, where six supply chain structures were defined and discussed. Literature stream 2 relates to strategy and performance improvement techniques. Based on the categorisation from stream 2 of the literature, section 2.7 discusses a categorisation of the different strategies for the ETO supply chain to emerge from the literature. Literature stream 3 relates to lean and agile approaches. Using the literature from stream 3, the relationship between lean and agile approaches with the ETO type is explored. Finally, research methods and sectors are identified and analysed. This is followed by a synthesis and an indication of future research directions.

2.4 METHOD FOR THE STRUCTURED LITERATURE REVIEW

2.4.1 Sampling

In order to review systematically the literature related to ETO supply chains, the first step was to develop a criterion for including papers in the review. Candidates for inclusion consisted of published journal articles, but not limited to particular journals. Key word searches were made through several databases including ABI Inform, EBSCO, internet searches, Google Scholar, Scopus, Science Direct and Emerald. Keywords included those highlighted in table 2.4. Level 1 keywords must appear in the articles, whereas level 2 keywords, used in conjunction with level 1 keywords, refined and narrowed the search criteria as well as helping to categorise papers. Once papers were identified, the references were reviewed to assist in locating additional papers, resulting in a snowball sampling effect. Journal papers were read and a decision as to whether the papers should be included rested on their contribution to questions and aims specified for the structured literature review. Three key questions were asked of each paper. Does it contribute to the development of definitions of the ETO type? Does it contribute to the development of strategy? Does it help to relate the lean and agile paradigms to the ETO type? Ninety one articles were identified by the databases and search engines combined. Although a number of books are also mentioned throughout this chapter in order to provide background material, these are not included in the classification.

Key words – Level 1	Keywords – Level 2
Engineer-to-order	Supply chain structure
Project	Supply chain
Design-to-order	Strategy
Build-to-order/Make-to-order	Lean/Leagile/Agile
Non make-to-stock	Construction/Capital Goods
One-of-a-kind	Flexibility
	Decoupling Point
	New Product Development Process
	Performance Improvement
	Case/Survey/Questionnaire/Model/Tool

Table 2.4: Keyword used in the literature search

2.4.2 Quality Assessment

In order to determine the perceived quality of the journals in which the papers appear the Association of Business Schools (ABS) "Academic Journal Quality Guide" (Harvey et al., 2007) has been utilised. This guide is widely adopted by business schools in the UK to judge the acceptability of articles in the UK's university sector Research Assessment Exercise in 2008. The guide synthesises a number of existing perception based survey results of the academic community as well as the ISI impact factor scores. Journals are then ranked according to a five point scoring system, with 4 being the highest and 0 the lowest. Journals are grouped according to discipline, namely Operations and Technology Management (OTM), Management Science and Operations Research (MSOR), General Management (GM), Information Systems and Management (IM), Research and Innovation (INNOV), Marketing (MKT) and Sectoral Studies (SCT). Where a journal does not appear in the guide it has been termed as unclassified (UC). Table 2.5 shows the different journals used in the study ranked by the number of papers appearing in this review.

Journal Title	Literature Stream Category: Stream 1: Supply Chain Structures	Stream 2: ETO Strategy	Stream 3: Lean and Agile	All
International Journal of Production Economics (OTM 3)	2	8	7	17
International Journal of Operations and Production Management (OTM 3)	2	6	3	11
International Journal of Production Research (OTM 3)	2	0	3	5
Construction Management and Economics (SCT 2)	0	3	2	5
Supply Chain Management: An International Journal (OTM 3)	0	3	1	4
Journal of Operations Management (OTM 4)	1	1	1	3
Sloan Management Review (UC)	1	1	1	3
European Journal of Purchasing and Supply Management (UC)	0	3	0	3
International Journal of Logistics (OTM 2)	1	1	1	3
Building Research and Information (UC)	0	1	2	3
Computers in Industry (UC)	1	2	0	3
International Journal of Project Management (OTM 2)	1	2	0	3
Housing Studies (UC)	0	0	2	2
Journal of Construction Engineering and Management (UC)	0	1	1	2
Production Planning & Control (OTM 2)	1	1	0	2
International Journal of Agile Management Systems (OTM 1)	0	0	2	2
Journal of Supply Chain Management (OTM 1)	0	1	0	1
Industrial Management & Data Systems (IM 1)	1	0	0	1
Industrial Marketing Management (MKT 3)	0	0	1	1
Integrated Manufacturing Systems (TOM 2)	1	0	0	1
Harvard Business Review (GM 3)	1	0	0	1
European Journal of Operational Research (MSOR 3)	0	1	0	1
European Journal of Innovation Management (INNOV 1)	0	1	0	1
Journal of Purchasing and Supply Management (OTM 2)	0	1	0	1
International Journal of Logistics Management (OTM 2)	0	0	1	1
International Journal of Computer Integrated Manufacturing (OTM 2)	0	1	0	1
Engineering, Construction and Architectural Management (SCT 1)	0	1	0	1
IEEE Transactions on Engineering Management (OTM 3)	0	1	0	1
Production and Inventory Management Journal (OTM 2)	0	1	0	1
Business Process Management Journal (OTM 1)	0	1	0	1
International Journal of Agile Manufacturing (UC)	0	0	1	1
International Journal of Agile Management (UC)	0	0	1	1
International Journal of Physical Distribution and Logistics (OTM 1)	0	0	1	1
European Management Journal (GM 1)	0	0	1	1
International Journal of Industrial and Systems Engineering	0	1	0	1
Journal of Manufacturing Technology Management (OTM 2)	0	0	1	1
Cumulative total	**15**	**43**	**33**	**91**

Table 2.5: Categorisation of the ETO literature

2.4.3 Categorisation

The papers reviewed are then categorised into three different streams of literature, which form the basis for the rest of the paper. The three streams are as follows:

- Stream 1 'Supply chain structures' – Papers that primarily focus on developing definitions or typologies for the ETO supply chain or a range of supply chain structures with reference to ETO supply chains.
- Stream 2 'Strategy' – Papers that primarily focus on strategies or performance improvement techniques specifically for ETO supply chains. Papers that explore strategies for non-MTS supply chains were also considered for this category.
- Stream 3 'Lean and Agile' – Papers that primarily focus on Lean or Agile aspects of ETO supply chains.

2.5 DEFINING THE ENGINEER-TO-ORDER SUPPLY CHAIN

2.5.1 Supply chain structures and the ETO supply chain

The importance of classifying supply chains according to particular markets and characteristics has been widely addressed in the supply chain literature. This section will review some of the key contributions. The frameworks reviewed in this section are often referred to as supply chain structures and propose to make sense of the diverse range of supply chain operations by showing how different parts of the supply chains interact with customer orders. Some papers, however, do not address the full range of supply chain structures and focus on a select few or one specific structure. These papers relate directly to stream 1.

The initial part of literature review identified and discussed six supply chain structures. The ETO supply chain structure was identified as one of these six structures. This structured literature review helps to integrate this stream of literature with other streams pertinent to the thesis. Papers that contribute to the development of the ETO structure are discussed in this section.

Ohlager (2003) simplified the classification of supply chain structures to include MTS, where the decoupling point is located at the shipment stage, ATO, where the decoupling point is located at the final assembly stage, MTO, where the decoupling point is located at the fabrication and procurement stage and ETO, where the decoupling point is located at the design stage. Ohlager (2003) built on previous work by developing a conceptual impact model for the factors affecting the positioning of the order penetration point.

Lampel and Mintzberg (1996) provided an important contribution to the supply chain body of knowledge by proposing a continuum of strategies to show how standardization and customization of products, processes and customer transactions can be rationalised. The continuum of strategies show how the level of standardisation and customisation for key processes, such as design, fabrication, assembly and distribution of products can be configured to produce five different strategies: pure standardisation, segmented standardisation, customised standardisation, tailored customisation and pure customisation. Yang and Burns (2003) developed this continuum of strategies and framed it within the postponement literature. Postponement centres around delaying activities in the supply chain until real information about the market is available. Lampel and Mintzberg's (1996) continuum is expanded to incorporate new processes, notably packaging, and a number of postponement strategies are included in the model.

A number of different ways of classifying manufacturing are explored by Porter et al. (1999). They suggested a number of different ways of thinking about different types of manufacturing, but most importantly, for this review, they proposed five classes of manufacturing MTS, ATO, MTO, ETO and design-to-order (DTO). ETO, in this case, is defined as a standard product range offered with the added availability of modifications and customisations. DTO is defined as where design, engineering and manufacturing are newly designed based on each new customer order. This distinction highlights a confusing aspect of the ETO supply chain whereby different authors have used different terms to distinguish between variations of the ETO type.

Table 2.6 offers an overview of the key variations in definitions across the different categories of literature.

	Literature Stream Category		
Definition	**Stream 1: Supply Chain Structures**	**Stream 2: ETO Strategy**	**Stream 3: Lean and Agile**
ETO supply chains have customised production dimensions with the decoupling point located at the design stage	*7* (Lampel and Mintzberg, 1996; Martínez-Olvera and Shunk, 2006; Olhager, 2003; Rudberg and Wikner, 2004; Samadhi and Hoang, 1995; Wikner and Rudberg, 2005; Yang and Burns, 2003)	*4* (Bertrand and Muntslag, 1993; Gann, 1996; Tersine and Hummingbird, 1995; Vrijhoef and Koskela, 2000)	*2* (Barlow, 1999; Cooney, 2002)
ETO supply chains offer customised products where existing designs are modified to order.	*4* (Amaro et al., 1999; Porter et al., 1999; Rudberg and Wikner, 2004; Wikner and Rudberg, 2005)	*3* (Bozarth and Chapman, 1996; Rahman et al., 2003b; Wadhwa et al., 2006)	*0*
ETO supply chains offer customised products where completely new designs are developed to order	*3* (Amaro et al., 1999; Rudberg and Wikner, 2004; Wikner and Rudberg, 2005)	*9* (Bertrand and Muntslag, 1993; Bozarth and Chapman, 1996; Chin-Sheng, 2006; Little et al., 2000; Rahman et al., 2003b; Vrijhoef and Koskela, 2000; Wacker and Miller, 2000; Wadhwa et al., 2006; Wortmann, 1995)	*0*
ETO supply chains operate in a project environment with project specific demands/One-of-a kind	*5* (Hameri, 1997; Hicks et al., 2001; Martínez-Olvera and Shunk, 2006; Samadhi and Hoang, 1995; Tu, 1997)	*11* (Cameron and Braiden, 2004; Caron and Fiore, 1995; Dainty et al., 2001a; Donselaar et al., 2001; Elfving et al., 2005; Gann, 1996; Hicks et al., 2000; Karkkainen et al., 2003; Thompson et al., 1998; Vrijhoef and Koskela, 2000; Wortmann, 1995; Yeo and Ning, 2002)	*1* (Sanderson and Cox 2008)

Table 2.6: Categorisation of the literature defining ETO supply chains

Many authors agree that all production dimensions are customised for each order in the ETO supply chain, that the decoupling point is located at the design stage, and that they operate in project specific environments. The lack of agreement is found in the extent to which existing designs are modified to order, or whether completely new designs are developed for each order. Furthermore, there is also a lack of clarity as to the appropriate terminology to use. Authors use different terms to describe very similar operating environments. Project (Elfving et al., 2005), craft (Barlow, 1999), one-of-a-kind (Hameri, 1997; Tu, 1997), DTO and ETO (Hicks et al., 2001) are frequently used in conjunction with supply chain, production, organisation and system to refer to the supply chain type that is investigated herein.

2.5.2 Segmenting ETO supply chains

Wikner and Rudberg (2005) proposed a useful framework to help overcome the confusion over the design aspect of ETO supply chains. They decoupled the engineering and production related activities of the supply chain and propose a non linear approach. An engineering dimension and production dimension were advocated with the engineering dimension ranging from ETO, where a new product is designed, and engineer to stock (ETS), where a design is already 'in stock'. Between ETO and ETS engineering modifications to existing product designs are used in varying degrees. This is consistent with observations elsewhere that ETO products can include varying degrees of standardised and customised bills of materials from order to order (Bozarth and Chapman, 1996; Hicks et al., 2000, 2001).

Various ETO types have also been proposed in the literature. Amaro et al. (1999) distinguished between the versatile manufacturing sector which are involved in a competitive bidding situation for every order and the repeat business customisers, which may receive a series of similar orders from particular customers. Furthermore, Amaro et al. (1999) suggested four types of ETO in their taxonomy of versatile manufacturing companies along with five types of MTO supply chain and two ATO. The commonality among the four ETO types is the 'pure' degree of customisation (a new design is produced to order), but the four different types vary in the amount of responsibility that is managed in-house, such as design and purchasing, and the number and type of activities that are completed after the receipt of an order, such as design, routing and purchasing. Hicks et al. (2001) also defined four ideal types of ETO companies: vertically integrated, design and assembly, design and contract and project management. All four types produce outputs with a deep product structure (high product complexity), but differ in the core competencies, source of competitive advantage, degree of vertical integration, supplier relationships, environment and types of risk.

From the review in this section, which focussed primarily on literature relating to literature stream 1, supply chain structures, it can be concluded that:

- There is a range of structures that describe the characteristics of different supply chains. The majority of models use the CODP as a way of distinguishing between different structures;
- There is a lack of clarity as to the appropriate terminology to use to describe the ETO supply chain type;
- ETO supply chain frameworks agree that the production flow is all driven by actual customer orders with the decoupling point located at the design stage, but disagree on the definitions for the design dimension. Some argue that ETO companies modify existing orders, while others argue that completely new designs are developed to order. Wikner and Rudberg's (2005) decoupling approach offers a useful starting point for considering the relationship between design and production dimensions;
- Several types of ETO system may exist. Amaro et al. (1999) and Hicks et al. (2001) both identified four different types of ETO organisations.

2.6 STRATEGIES FOR ETO SUPPLY CHAINS

This section will now review the literature that has specific relevance to developing strategies for the ETO sector. These papers have been classified as literature stream 2, strategy. Literature stream 2 also includes, where appropriate, literature relating to strategies for the build-to-order sector as a whole. The classification illustrated in Table 2.7 outlines the main themes from this category and the linkages with the other two categories of literature.

	Literature Stream Category		
Strategy	Stream 1: Supply Chain Structures	Stream 2: ETO Strategy	Stream 3: Lean and Agile
Shift between supply chain structure to suit marketplace/ Standardisation/ Reduce complexity.	*7* (Lampel and Mintzberg, 1996; Martínez-Olvera and Shunk, 2006; Olhager, 2003; Rudberg and Wikner, 2004; Wadhwa et al., 2006; Wikner and Rudberg, 2005; Yang and Burns, 2003)	*9* (Barlow et al., 2003; Gann, 1996; Hicks et al., 2000; Holweg and Pil, 2001; Ireland, 2004; Jahnukainen and Lahti, 1999; Krajewski et al., 2005; Voordijk et al., 2006; Wacker and Miller, 2000)	*5* (Ballard and Howell, 1998; Barlow, 1999; Christopher and Towill, 2002; Naylor et al., 1999)
Supply chain Integration	*1* (Hicks et al., 2001)	*14* (Caron and Fiore, 1995; Cox and Thompson, 1997; Dainty et al., 2001a; Elfving et al., 2005; Hicks et al., 2000, 2001; Ireland, 2004; Jahnukainen and Lahti, 1999; Kingsman et al., 1996; Parker et al., 2008; Thompson et al., 1998; Vrijhoef and Koskela, 2000; Yeo and Ning, 2002)	*7* (Christopher, 2000; Christopher and Towill, 2002; Cox and Chicksand, 2005; Narasimhan et al., 2006; Naylor et al., 1999; Storey et al., 2005; Vonderembse et al., 2006)
Information Management	*3* (Hameri, 1997; Porter et al., 1999; Tu, 1997)	*9* (Bertrand and Muntslag, 1993; Corti et al., 2006; Donselaar et al., 2001; Ebadian et al., 2008; Gelders, 1991; Karkkainen et al., 2003; Little et al., 2000; Wortmann, 1995; Zorzini et al., 2008)	*3* (Christopher, 2000; Naylor et al., 1999; Storey et al., 2005)
Business Systems Engineering /Business Process Re-engineering.	*0*	*4* (Cameron and Braiden, 2004; Childerhouse et al., 2003b; McGovern et al., 1999; Towill, 2001)	*0*
Flexibility	*3* (Martínez-Olvera and Shunk, 2006; Tu, 1997; Wadhwa et al., 2006)	*5* (Coronado and Lyons, 2007; Gann, 1996; Gil et al., 2005; Holweg and Pil, 2001; Krajewski et al., 2005; Salvador et al., 2007)	*4* (Christopher and Towill, 2002; Cooney, 2002; Narasimhan et al., 2006; Naylor et al., 1999)
Time Compression	*0*	*6* (Bozarth and Chapman, 1996; Chin-Sheng, 2006; Elfving et al., 2005; Handfield, 1994; Tersine and Hummingbird, 1995; Towill, 2003)	*3* (Christopher, 2000; Mason-Jones and Towill, 1999; Naylor et al., 1999)
New Product Development Process Improvement	*0*	*3* (Caron and Fiore, 1995; Karkkainen et al., 2001; Rahman et al., 2003b)	*0*

Table 2.7: Summary of strategies for ETO supply chains

Shift between supply chain structures

There is a large body of literature that promotes the movement from a MTS strategy to a BTO strategy to gain competitive advantage (Gunasekaran and Ngai, 2005; Hicks et al., 2001; Salvador et al., 2007). A much smaller body of knowledge exists that has explored organisations and supply chains that operate in markets that dictate a BTO or ETO approach. Amaro et al (1999) highlighted that the ability to customise is not always necessarily a source of competitive advantage, in pure customisation markets it may only qualify an organisation to operate in such markets. A possible strategy to manage the diverse product variety in the ETO sector is to forward shift through supply chain structures via modularity. In the house building and commercial sector there have been moves to forward shift through the supply chain structures by adopting modular design and greater standardisation of supply chain activities (Barlow et al., 2003; Voordijk et al., 2006). Hicks et al. (2000), researching the capital goods sector, found that modular configurations and standard items can reduce costs and lead times.

Supply chain integration

Addressing supply chain management for ETO systems, Vrijhoef and Koskela (2006) suggested four roles that are pertinent to construction: improving the interface between site activities and the supply chain, improving the supply chain, transferring activities from the site to the supply chain and integration of site and the supply chain. Jahnukainen and Lahti (1999) argued that JIT and supplier development initiatives from high volume sector can be used, such as reduction of suppliers, deeper and longer lasting relationships and suppliers controlled as part of in-house manufacturing. Hicks et al. (2000) emphasized that some lessons can be learnt from the high volume sector, such as reduction of the supplier base and long term relationships, but that the characteristics of ETO markets significantly constrain the application of established supply chain management methods. Briscoe and Dainty (2005) found that the large number of supply chain partners and the significant level of fragmentation in the construction environment place constraints on the level of supply chain integration that is achievable. Ireland (2004) concluded that demand regularity and power regimes are the key variables dictating which supply chain management techniques are suitable and those which are not.

Information Management

Van Donselaar et al. (2001) concluded that advanced demand information, even if incomplete and imperfect, can help manufacturers in a project supply chain reduce their demand uncertainty. This helps manufacturers to reduce the stock of finished goods. Karkkainen et al. (2003) explored the potential of utilising web and product identification technologies to overcome logistical challenges of a project supply chain. They concluded that many benefits can be gained from using an identity based system for tracing, tracking and control of project deliveries. Research examining information management systems for production control of ETO systems has also been published. Bertrand and Muntslag (1993) and Little et al. (2000) addressed the failure of the Material Resource Planning (MRP) production control system to effectively manage an ETO system. They suggest that the characteristics of an ETO system differ substantially from the basic assumptions of MRP. Both papers propose different production control systems to take into account the high level of uncertainty and customer specific product specifications. Wortman (1995) compares the information systems for a MTS and an ETO system and suggested that information and production systems for an ETO supply chain should allow for basic information to be incomplete, partly inconsistent, or not up to date.

Business Systems Engineering

Business Systems Engineering (BSE) and Business Process Re-engineering (BPR) have also been proposed as routes to improving the ETO sector. Towill (2001) applied the Understand, Document, Simplify and Optimise (UDSO) BSE routine to a Doyle Wilson case study to demonstrate a successful application of the systems approach by a housing contractor. Childerhouse et al. (2003b) provided a case study to show best practice for business process re-engineering and cycle time compression in construction. They demonstrated how a BPR programme yielded substantial improvements in measures such as cycle times, delivery frequencies, stock turns, profit margin and annual volume. BPR was carried out across four different areas: JIT manufacturing, reducing lead times, supplier integration and customer integration. However, Cameron and Braiden (2004), when applying BPR techniques to four different ETO companies, found some difficulties emerged when trying to apply BPR in the ETO sector. Redesigning processes within functional areas was found to be useful and easy but difficulties increased when functional boundaries and supply units were crossed. The absence of risk assessments in BPR methodologies was also noted as a key constraint for its application in the ETO sector.

Flexibility

Flexibility has been considered as crucial to ETO strategy. Salvador et al. (2007) highlighted the importance of volume and mix flexibility in implementing a BTO system. In particular they highlight product flexibility, assembly flexibility, workforce flexibility and supplier flexibility. However, they suggest that there are tradeoffs and synergies associated with different types of flexibility. Holweg and Pil (2001) suggested that the three dimensions of a successful BTO strategy are process flexibility, product flexibility and volume flexibility. Krajewski et al. (2005) explored the flexibility strategies suppliers use to respond to schedule changes in BTO supply chains and argue that two distinct strategies have emerged from the case studies examined, 'reduce uncertainty' and 'cope with uncertainty'. Tu (1997) also suggested that one-of-a-kind production companies require flexible or dynamic control structures and adaptable production scheduling. The flexibility literature is important for this thesis and Part 3 of the literature review will explore the flexibility body of knowledge in greater depth.

Time Compression

The application of time compression principles has been proposed to improve ETO supply chains. The importance of time compression is highlighted in Towill's (2003) conclusion that a 40% reduction in project time can lead to a 25% reduction in total work undertaken and costs. In particular, procurement and the competitive bidding, as well as the design stage have been highlighted as being time bottlenecks for ETO supply chains (Elfving et al., 2005; Gosling et al., 2007a). In addition, concurrent engineering has been suggested as a way of reducing the time to market in a MTO system (Babu, 1999).

New Product Development Process Improvement

Rahmin et al. (2003b) suggested that ETO companies can achieve business objectives more effectively by reducing design iterations and rework, recognizing customers' requirements up-front and building quality into design and manufacturing. They analysed existing frameworks from published literature and find that existing frameworks are not suitable for ETO companies. They proposed a set of requirements for establishing a design and manufacture framework specifically for ETO companies. Caron and Fiore (1995) explored the integration of product development processes in the ETO system and its integration with logistics and project management. They suggested that taskforces help to facilitate information exchange between the design and manufacture stages.

From the review in this section it can be concluded that:

- Research relating to strategies for ETO supply chains can be classified under six different categories: shift between supply chain structures, supply chain integration, information management, business systems engineering, flexibility, time compression and new product development process improvement;
- Strategies for organisations operating in low volume, highly customised, ETO environments have received much less attention from researchers than high volume, standardised, MTS environments;
- Some supply chain management and BPR techniques may be appropriate for ETO supply chains but confusion exists as to which may be suitable. The variables offered by Ireland (2004), demand regularity and power regimes, are useful for considering which strategies are appropriate or not;
- Various types of flexibility are required to compete effectively in a BTO or ETO supply chain but there are no agreements on what types of flexibilities are required, or if there are synergies or tradeoffs between them.

2.7 LEAN AND AGILE PARADIGMS AND THE ENGINEER-TO-ORDER SUPPLY CHAIN

This review has now covered literature relating to supply chain structures and literature relating specifically to the ETO or BTO strategies. This section will synthesize literature related to two the paradigms discussed in Part 1 of the literature review: lean thinking and agile manufacturing. Table 2.8 summarises some of the key literature relating to this area.

	Literature Stream Category		
Theme	**Stream 1: Supply Chain Structures**	**Stream 2: ETO Strategy**	**Stream 3: Lean and Agile**
Definitions / Integrating Lean and Agile	*0*	*1* (Gann, 1996)	*15* (Christopher, 2000; Christopher and Towill, 2001; Gunasekaran, 1999; Hines et al., 2004; Katayama and Bennett, 1999; Mason-Jones et al., 2000; Narasimhan et al., 2006; Naylor et al., 1999; Papadopoulou and Özbayrak, 2005; Sanchez and Nagi, 2001; Sanderson and Cox, 2008; Sharp et al., 1999; Vonderembse et al., 2006; Yusuf and Adeleye, 2002; Yusuf et al., 1999)
Match supply chains strategies to your market place / Agile suitable for non make-to-stock structures whereas lean suitable for make-to-stock structures	*9* (Fisher, 1997; Gunasekaran and Ngai, 2005; Lampel and Mintzberg, 1996; Martínez-Olvera and Shunk, 2006; Olhager, 2003; Rudberg and Wikner, 2004; Wadhwa et al., 2006; Wikner and Rudberg, 2005; Yang and Burns, 2003)	*1* (Gann, 1996)	*5* (Christopher, 2000; Mason-Jones et al., 2000; Naylor et al., 1999; Towill et al., 2002; Vonderembse et al., 2006)
Critique of the Applicability of Lean	*0*	*2* (Gann, 1996; Ireland, 2004)	*4* (Cooney, 2002; Cox and Chicksand, 2005; Cusumano, 1994; Green, 1999)
One Paradigm fits in another	*0*	*1* (Holweg, 2005)	*5* (Hines et al., 2004; Narasimhan et al., 2006; Papadopoulou and Özbayrak, 2005; Storey et al., 2005; Van-Hoek, 2000)
Lean ETO Supply Chains.	*1* (Tu, 1997)	*4* (Chin-Sheng, 2006; Elfving et al., 2005; Gann, 1996; Ireland, 2004)	*4* (Ballard and Howell, 1998, 2002; Barlow, 1999; Naim and Barlow, 2003)
Agile ETO Supply Chains.	*1* (Tu, 1997)	*2* (Chin-Sheng, 2006; Ireland, 2004)	*5* (Babu, 1999; Barlow, 1999; Barlow and Ozaki, 2003; Gosling et al., 2007a; Naim and Barlow, 2003)

Table 2.8: Lean and Agile Strategies and the ETO supply chain

Numerous guidelines for the application of lean and agile paradigms have been suggested. A common approach is the use of supply chain structure concepts to help determine their applicability. The literature suggests that increasing levels of leanness are appropriate moving towards the STS structure, where products and processes are more standardised, and increasing levels of agility are appropriate moving towards the opposite end of the spectrum towards the ETO structure, where products and processes are more customised (Christopher, 2000; Gosling et al., 2007b; Naylor et al., 1999). It is also worth noting that a combination of the approaches, leagility, has been proposed and is more commonly associated with the ATO supply chain structure (Mason-Jones et al., 2000; Naylor et al., 1999; Van-Hoek, 2000).

Both lean and agile strategies have been proposed in the ETO sector. Koskela (1992) proposed that the construction industry needed to adopt a new production philosophy based on the emerging methodologies, techniques and tools associated with lean production. Similarly, the Egan Report (1998) argued that lean principles, such as standardisation, JIT and long term partnerships with suppliers should be adopted. The International Group for Lean Construction (IGLC) has also been formed and numerous researchers have attempted to define and research 'lean construction'. However, the extent to which lean principles are suitable in the ETO or BTO environment has been questioned (Cooney, 2002).

Agility has also been suggested as a suitable strategy for the BTO and ETO sector, but has received less attention. Agility has been proposed as a strategy in the BTO manufacturing literature (Babu, 1999; Gunasekaran and Ngai, 2005), and as a good conceptual fit with the characteristics of the ETO supply chain (Gosling et al., 2007b). Agility has also been proposed in the construction sector (Barlow, 1999; Naim and Barlow, 2003). In summary, although there is a good conceptual fit between agility and the ETO sector there is little empirical testing available to draw firm conclusions.

From the review in this section it can be concluded that:

- There are disagreements as to the boundaries, definitions and applicability of leanness and agility;

- Lean, agile and leagile strategies can be mapped onto supply chain structures to help determine their applicability. This approach would suggest that agility is more suited to the ETO supply chain and leanness to a STS supply chain;
- Both lean and agile strategies have been proposed in the literature as strategies for the ETO and BTO sector, but there is no clear answer regarding their applicability.

2.8 RESEARCH METHODOLOGY AND SECTORIAL ANALYSIS

2.8.1 Research Methods

Although the overall sample is quite small it is still possible to make some generic observations of the results within a methodological framework. Table 2.9 shows a summary of the different research methods used in the different streams of literature. The ETO literature streams support Burgess et al. (2006), who highlighted the relative immaturity of supply chain management research and the need to further understand the landscape of supply chain management. This is reflected in the dominance of conceptual and case study approaches with much less research undertaking large scale questionnaires or surveys.

Across all three streams of literature there is a shortage of focus group research and questionnaire research contributing to the development of the ETO type. Conceptual and case study research account for the majority of papers in the review. Dainty et al. (2001) provided the only use of focus groups across all streams. They used a mixture of focus groups and interviews to identify the barriers to supply chain integration. Tools and models are well represented in the strategy literature stream but are not so well represented in the other two streams.

Method	Literature Stream Category Stream 1: Supply Chain Structures	Stream 2: ETO Strategy	Stream 3: Lean and Agile
Conceptual	*9* (Gunasekaran and Ngai, 2005; Lampel and Mintzberg, 1996; Martínez-Olvera and Shunk, 2006; Olhager, 2003; Porter et al., 1999; Rudberg and Wikner, 2004; Samadhi and Hoang, 1995; Wikner and Rudberg, 2005; Yang and Burns, 2003)	*11* (Bozarth and Chapman, 1996; Chin-Sheng, 2006; Cox and Ireland, 2002; Cox and Thompson, 1997; Gelders, 1991; Holweg and Pil, 2001; Karkkainen et al., 2003; Tersine and Hummingbird, 1995; Towill, 2003; Wacker and Miller, 2000; Yeo and Ning, 2002)	*13* (Babu, 1999; Christopher, 2000; Cusumano, 1994; Green, 1999; Gunasekaran, 1999; Hines et al., 2004; Mason-Jones et al., 2000; Mason-Jones and Towill, 1999; Sanchez and Nagi, 2001; Towill et al., 2002; Van-Hoek, 2000; Vonderembse et al., 2006; Yusuf et al., 1999)
Primary case study	*4* (Amaro et al., 1999; Hameri, 1997; Hicks et al., 2001; Wadhwa et al., 2006)	*19* (Barlow et al., 2003; Childerhouse et al., 2003b; Coronado and Lyons, 2007; Dainty et al., 2001a; Donselaar et al., 2001; Elfving et al., 2005; Gann, 1996; Gil et al., 2005; Handfield, 1994; Hicks et al., 2000; Ireland, 2004; Jahnukainen and Lahti, 1999; Krajewski et al., 2005; McGovern et al., 1999; Salvador et al., 2007; Thompson et al., 1998; Voordijk et al., 2006; Vrijhoef and Koskela, 2000; Zorzini et al., 2008)	11 (Ballard and Howell, 1998; Barlow, 1999; Barlow and Ozaki, 2003; Cooney, 2002; Cox and Chicksand, 2005; Holweg, 2005; Naim and Barlow, 2003; Naylor et al., 1999; Papadopoulou and Özbayrak, 2005; Sanderson and Cox, 2008; Storey et al., 2005)
Focus Groups	*0*	*2* (Cameron and Braiden, 2004; Dainty et al., 2001a)	0
Survey / Questionnaire	*0*	*2* (Little et al., 2000; Parker et al., 2008)	*4* (Katayama and Bennett, 1999; Narasimhan et al., 2006; Sharp et al., 1999; Yusuf and Adeleye, 2002)
Tool/Model	*1* (Tu, 1997)	*11* (Bertrand and Muntslag, 1993; Cameron and Braiden, 2004; Caron and Fiore, 1995; Corti et al., 2006; Ebadian et al., 2008; Karkkainen et al., 2001; Kingsman et al., 1996; Little et al., 2000; Rahman et al., 2003b; Towill, 2003; Wortmann, 1995)	*3* (Ballard and Howell, 2002; Christopher and Towill, 2001; Christopher and Towill, 2002)

Table 2.9: Emerging research methods from the ETO literature

Stream 1 is largely conceptual with only a few papers making use of secondary case studies to highlight differences between supply chain structures. All other types have little or no representation. Notable exceptions here include Whadhwa et al.'s (2006) use of automotive case studies to develop postponement strategies, Amaro et al.'s (1999) 22 case studies of non MTS companies including 4 ETO firms and Hicks et al.'s (2001) study of five ETO companies. Stream 2 is well represented by case research, conceptual and tools/model development. Survey and focus group research are not well represented. Finally, stream 3 is well represented by conceptual and case research but less so in all other research methods.

2.8.2 Sector Analysis

Table 2.10 illustrates the different sectors that have been studied in the ETO literature streams. Overall, construction is the dominant sector for the ETO literature, followed by capital goods. Stream 1 is mostly conceptual and focuses on generic types of supply chains rather than specific sectors. Stream 2, ETO strategy, is concentrated around the construction and capital goods industries. However, there are notable exceptions in the high tech industry, automotive and consumer electronics. Stream 3 shows a more varied profile with lean and agile paradigms being explored across a wide range of industries. High tech and capital goods industries are not represented in stream 3, but it is the only stream to include a paper from the shipbuilding industry (Sanderson and Cox, 2008). Defillipi and Arthur's (1998) analysis of the film making industry highlights that there are many industries, including law cases, software writing and shipbuilding that share similar underlying ETO characteristics. Empirical research relating these sectors to the wider ETO body of literature would contribute significantly to the development of the ETO type.

Sector	Literature Stream Category Stream 1: Supply Chain Structures	Stream 2: ETO Strategy	Stream 3: Lean and Agile
Construction	*0*	*13* (Barlow et al., 2003; Childerhouse et al., 2003b; Cox and Ireland, 2002; Cox and Thompson, 1997; Dainty et al., 2001a; Elfving et al., 2005; Gann, 1996; Gil et al., 2005; Ireland, 2004; Thompson et al., 1998; Towill, 2003; Towill, 2001; Voordijk et al., 2006; Vrijhoef and Koskela, 2000)	*6* (Ballard and Howell, 1998, 2002; Barlow, 1999; Barlow and Ozaki, 2003; Green, 1999; Naim and Barlow, 2003)
High Tech	*0*	*1* (Caron and Fiore, 1995)	0
Investment/ Capital goods	*1* (Hicks et al., 2001)	*6* (Cameron and Braiden, 2004; Hicks et al., 2000; Jahnukainen and Lahti, 1999; Little et al., 2000; McGovern et al., 1999; Salvador et al., 2007)	0
Automotive	*0*	*2* (Holweg and Pil, 2001; Wadhwa et al., 2006)	*4* (Cooney, 2002; Cusumano, 1994; Holweg, 2005; Vonderembse et al., 2006)
Shipbuilding	*0*	*0*	*1* (Sanderson and Cox 2008)
Retail	*0*	*0*	*3* (Cox and Chicksand, 2005; Mason-Jones and Towill, 1999; Storey et al., 2005)
Consumer Electronics	*0*	*2* (Donselaar et al., 2001; Holweg and Pil, 2001)	*3* (Holweg, 2005; Naylor et al., 1999; Vonderembse et al., 2006)
General Manufacturing	*1* (Amaro et al., 1999)	*2* (Coronado and Lyons, 2007; Parker et al., 2008)	*5* (Katayama and Bennett, 1999; Narasimhan et al., 2006; Papadopoulou and Özbayrak, 2005; Sharp et al., 1999; Yusuf and Adeleye, 2002)

Table 2.10: Sector analysis of ETO supply chains

2.9 SYNTHESIS

Literature stream 1 was primarily used to identify the unique characteristics of ETO supply chains (see section 2.6). Literature stream 2 was primarily used to identify the strategies for ETO supply chains (see section 2.7). Literature stream 3 was primarily used to investigate the relationship between lean and agile paradigms and the ETO supply chain (see section 2.8). The different literature streams have been integrated in each section to identify links between the literature streams. Section 2.9 discussed the research methods used across all 3 literature streams. Figure 2.3 shows a summary of responses developed in this paper to the research questions posed in the structured literature review. These findings emerge from the preceding discussion of the 3 different literature streams. Based on these findings, four recommendations are proposed for future investigation of the ETO supply chain. These recommendations are now discussed in turn.

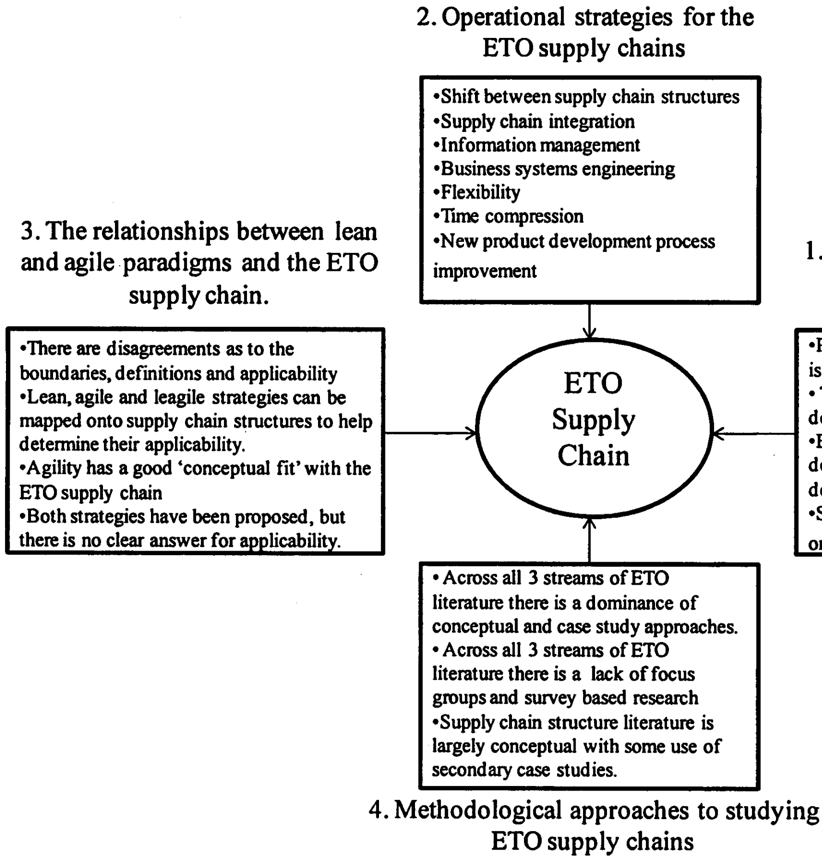


Figure 2.3: Synthesis of structured literature review

2.9.1 Towards a comprehensive definition of the ETO supply chain

The first objective of the structured literature review was to identify the unique characteristics of the ETO supply chain. The supply chain structure stream of literature characterises the ETO supply chain as one of a number of supply chain structures, which has a high degree of customisation when compared with other structures. The strategy stream of literature has also contributed to the development of definitions for the ETO supply chain by describing contexts and industrial sectors while exploring ETO strategy. This review has helped to highlight some of the commonalities of ETO types and some of the differences between ETO types in different sectors. The commonalities are that the ETO supply chain operates in a project environment and that each product is different to the last. Production dimensions of the supply chain are completely customised and the decoupling point is located at the design stage. The differences are that existing designs maybe modified-to-order or completely new designs are developed-to-order. There may also be sector specific differences. For example, each construction project has to be completed on a new site, whereas shipbuilding may take place at a fixed location.

2.9.2 Tailoring strategies for the ETO sector

The second objective of the structured literature review was to identify operational strategies have been proposed to improve performance in the ETO sector. Research relating to strategies for ETO supply chains has been classified under six different categories in this paper: shifting between supply chain structures, supply chain integration, information management, business systems engineering, flexibility, time compression and new product development process improvement. The review also suggests that some strategies may be more appropriate for ETO supply chains while others may be less suitable. For example, research relating to supply chain integration and BPR techniques has received mixed conclusions from researchers. It is also unclear as to whether the strategy of shifting through supply chain structures undermines the strategic advantage gained from offering customisation to clients and customers. Information management, flexibility, time compression and new product development process improvement have a greater level of consensus regarding their appropriateness.

2.9.3 Identifying appropriate applications of lean and agile paradigms in the ETO sector

The third objective of the structured literature review was to identify the relationship between lean and agile paradigms and the ETO supply chain. Both lean and agile strategies have been proposed in the literature as strategies for the ETO and BTO sector, but there is no clear answer regarding their applicability. Indeed, this review has highlighted that there are broad disagreements as to the boundaries, definitions and applicability of leanness and agility across many different sectors. In some cases supply chain structures have been used to help determine their applicability. These studies suggest that agility may be more suited to the ETO supply chain and leanness to STS supply chains, but there is little empirical research testing this proposition. More empirical research examining the extent to which lean and agile paradigms apply to different sectors and supply chain structures would strengthen the ETO body of knowledge.

2.9.4 A range of methodological approaches

The fourth objective of the structured literature review was to identify the methodological approaches that have been utilised to study ETO supply chains. Literature stream 1, relating to supply chain structures, is largely conceptual with some use of secondary case studies. Literature stream 2 is well represented in conceptual studies, case study research and tool/model development, but is not well represented by focus groups and survey research. Literature stream 3 is well represented by conceptual and case study research, and less well represented by focus groups, survey and tool/model development. Across all 3 literature streams there is a dominance of conceptual and case study approaches. There is also a lack of focus group and survey based methods. Research addressing the gaps in these literature streams is encouraged to achieve coverage from a broad range of methodological perspectives.

2.10 IMPLICATIONS FOR THE THESIS

From the structured literature review it can be conclude that the ETO supply chain operates in a project environment and that each product is different to the last. Production dimensions of the supply chain are completely customised and the decoupling point is located at the design stage. The differences are that existing designs maybe modified-to-order or completely new designs are developed-to-order. However, there may be specific differences between different ETO sectors.

The structured literature review has provided a framework to understand the developments that have emerged in the literature relating specifically to the ETO supply chain as well as providing a theoretical grounding for this thesis. There are a number of important implications for this thesis. Firstly, all 3 literature streams support the need to tailor strategies to the ETO supply chain. Literature stream 2 highlights that there is no consensus as to which strategies may be the most appropriate. Literature stream 3 highlights the lack of empirical investigation of lean and agile approaches to the ETO sector. Secondly, there is a lack of focus group research across all 3 literature streams. Finally, flexibility has been considered as important for a BTO and ETO strategy, but the flexibility types required, and the tradeoffs and synergies between different flexibility types, are unclear. The flexibility literature is addressed in more details in the next part of the literature review.

2.11 SUPPLY CHAIN UNCERTAINTY

Uncertainty can be defined as "a state or condition, ranging from falling short of certainty to an almost complete lack of conviction or knowledge about an outcome or result" (Merriam-Webster, 2009). Uncertainties affecting supply chain operations are recognized as significant obstacles to achieving value for customers. As a result, researchers in the field of operations management and supply chain management have examined sources and types of supply chain uncertainty and strategies to cope with such uncertainties (Childerhouse and Towill, 2004; Mason-Jones and Towill, 1998; Prater et al., 2001; van der Vorst and Beulens, 2002; Wilding, 1998). While it has been acknowledged that different types of supply chains are associated with different uncertainty profiles, the supply chain uncertainty literature has not addressed the particular sources of uncertainty and risk related to the ETO supply chain. Furthermore, the supply chain uncertainty circle has been successfully applied in a range of sectors, but there are no applications in the construction sector. This prompts the second research question.

Research Question 2: How can the sources of uncertainty in ETO construction supply chains be identified and categorized?

Davis (1993) suggests that the underlying problem when managing complex networks is "the uncertainty that plagues them". Geary et al. (2002) support this by asserting that "uncertainty rules the supply chain". A considerable amount of research exists on identifying and managing uncertainty in supply chain management (Childerhouse and Towill, 2004; Geary et al., 2002; Mason-Jones and Towill, 1998; van der Vorst and Beulens, 2002; Wilding, 1998). Understanding the sources of supply chain uncertainty and managing these uncertainties is clearly of interest to researchers and practitioners alike.

Uncertainty and risk are very often confused or used interchangeably. In this thesis a distinction is made between the two. Raftery (1994) suggested that risk is generally taken to have quantifiable attributes, whereas uncertainty does not, and that risks are insurable, whereas uncertainties are not. He also proposes a continuum with risks on one extreme, quantifiable, data driven and open to statistical testing, and uncertainties at the other, based on subjective probability and informed opinion. This is supported by Rodrigues et al. (2008) who argued that risk is a function of outcome and probability and hence it is something that can be estimated; uncertainty, on the other hand, occurs when decision makers cannot estimate the outcome of an event or the probability of its occurrence. The two concepts are clearly closely related and intertwined. Uncertainty increases risk and risk is a consequence of uncertainty.

Managing risk has emerged as an important topic in supply chain management. This is due to a number of trends, including the increase in strategic outsourcing, the globalization of markets, the increasing reliance on suppliers for specialized capabilities and innovation, and the reliance on supply networks for competitive advantage (Narasimhan and Talluri, 2009). While these trends offer innovative strategies for firms, they also increase the potential and magnitude of supply chain risk (Blackhurst et al., 2005). Supply chain risk comes in many different forms. Harland et al. (2003) classified these as strategic, operations, supply, customer, asset impairment, competitive, reputation, financial, fiscal, regulatory and legal risks. Chopra and Sohdi (2004) defined different categories of supply risk, including disruptions, delays, systems, forecast, intellectual property, procurement, receivables, inventory and capacity in their classification. Juttner et al. (2005) defined the basic constructs of supply chain risk management as supply chain risk sources, risk consequences, risk drivers and risk mitigation strategies. They argued that supply chain risk comprise "any risks for the information, material and product flows from original supplier to the delivery of the final product for the end user" (Juttner et al., 2005: p 200).

The argument that supply chain agility not only allows firms to respond efficiently and effectively to unanticipated changes in the marketplace, but also works as a risk mitigation strategy in managing anticipated and actual risks has been proposed by a number of researchers (Chopra and Sodhi, 2004; Christopher, 2000; Narasimhan and Talluri, 2009). Braunscheidel and Suresh (2009) found that agility and its antecedents is a disruption risk management tactic that enables the firm and its partners to respond rapidly to market place changes, and to respond rapidly to both potential and actual disruptions in the supply chain. Juttner et al. (2005) and Chopra and Sodhi (2004) both emphasized flexibility as a risk mitigation strategy.

A useful definition of supply chain uncertainty is offered by van der Vorst and Beulens (2002): supply chain uncertainty refers to "decision making situations in the supply chain in which the decision maker does not know definitely what to decide as he is indistinct about the objectives; lacks information about its environment or the supply chain; lacks information processing capacity; is unable to accurately predict the impact of possible control actions on supply chain behaviour; or, lacks effective control actions". Supply chain uncertainty can lead to over-reactions, unnecessary interventions, second guessing, mistrust and distorted information flows (Childerhouse et al., 2003a; Christopher and Lee, 2004).

These observations highlight the need to effectively anticipate, identify, classify and assess supply chain uncertainty.

Mason-Jones and Towill (1998), building on Davis (1993), developed the uncertainty circle model to conceptualize the different sources of uncertainty that affect supply chain performance. The uncertainty circle classifies supply chain uncertainty into four general types: process, supply, demand and control. Process uncertainty affects internal abilities to meet a target. Supply uncertainty results from poorly performing suppliers handicapping value adding processes. Demand uncertainty is associated with specific customers in relation to schedule variability and transparency of information flow. It also refers to the difference between the end marketplace demand and orders placed by customers. Control uncertainty affects the ability to transform customer orders into targets and supplier raw material requests. It has subsequently been refined and applied in a number of different ways (Childerhouse and Towill, 2004; Sanchez-Rodrigues et al., 2008; Towill et al., 2002) and, therefore, it is considered as a suitable and robust basis for categorizing the disturbances encountered in an ETO system, and for contrasting against other supply chain types and sectors.

2.11.1 Supply chain uncertainty and the pipeline

The phrase 'pipeline management' was originally coined by Forrester (1961) to describe the controlled flow of goods on demand. The pipeline has since been defined as the delay between an order being generated and the delivery of that order (Berry et al., 1998; Mason-Jones et al., 1997). Christopher (2005) referred to pipeline management as "the process whereby manufacturing and procurement lead times are linked to the needs of the marketplace" (p 154). Mason-Jones and Towill (1998) proposed that all supply chains have two distinct pipeline lead times. The first is the order-to-raw-material supplier information transfer pipeline. The second is the product transfer pipeline from raw material to customer. Orders flow upstream and, as a direct consequence, products flow downstream. In traditional supply chains individual companies have very little direct visibility of what is happening anywhere else in the supply chain.

The importance of pipeline management has been confirmed by a number of studies. Sterman (1989) found that the inclusion of pipeline information in a master production schedule ordering rule can have a dramatic impact on improving dynamic behaviour and reducing uncertainty. The findings of Berry et al. (1998) support this. A lack of consideration of the pipeline can lead to costly swings in supply, production and inventory, which in turn can lead to periods of poor customer service and excessive stock. Mason-Jones et al. (1997) argued that it is essential that ordering systems include pipeline feedback at every echelon of the supply chain. Typically, in a four level chain, demand amplification can be halved by divulging marketplace data throughout the pipeline in a timely manner. Christopher (2000) argued that lengthy and slow moving pipelines are unsustainable. The goals of pipeline management are lower costs, higher quality, more flexibility and faster response times. Two key strategies are, first, to reduce the length of the pipeline and, second, speed up the flow through that pipeline (Christopher, 2005).

According to Christopher (2005), short lead times themselves are a source of competitive advantage, but the reliability or consistency of lead times are equally important. Due to bottlenecks, inefficient processes and fluctuations in the volume of orders handled, there will often be considerable variation in the time taken for pipeline activities to be completed. The overall effect can be a substantial reduction in the reliability of delivery. Davis (1993) highlighted the importance of understanding variability from the supply side, both by degree of inconsistency as measured by standard deviation and the root cause of these variations. It is also important to understand the buying organisation's response to this variability in terms of safety stocks, ordering policies and collaborative arrangements.

There is also a significant amount of literature concerned with lead time analysis and reduction. Schmenner (2001) proposed a theory of "swift, even flow", with a focus on increasing speed and reduction of variability. Time based competition advocates a competitive strategy purely based on speed (Hum and Sim, 1996; Rich and Hines, 1997; Stalk, 1988). Cycle time compression is based on the assumption that collapsing lead times can lead to improved demand forecasting, quicker defect detection, quicker to market and a shifting of the decoupling point towards the customer (Towill, 1996). It has also been noted that agility requires the slashing of process lead time throughout the supply chain (Mason-Jones and Towill, 1997).

Much of the research on pipelines has been conducted in high volume manufacturing sectors. Sanderson and Cox (2008) concluded that complex project environments introduce radical unpredictability into functional pipelines, which should demonstrate stable demand patterns. Elfving et al. (2005) found that project based production has characteristics, such as competitive bidding, which stifle attempts at radical reduction in lead time. Project supply chains may be part of existing, longer lived supply chains that operate regardless of whether or not any one particular project exists. Alternatively, project supply chains may be established specifically to meet one, or a small number of, project needs (Tommelein et al., 2009). Pipelines in project environments, therefore, may operate under different constraints and conditions than those in high volume make-to-stock structures. Hence, an understanding of the pipeline is important for the study of ETO supply chains.

Berry et al. (1998) found that it is still common to find companies operating under uncertainty as they have not adequately addressed the pipeline. Until pipelines are analysed and re-engineered it is likely that they will experience protracted and variable lead times. Christopher and Towill (2002) noted that a philosophy of 'one size fits all' does not apply to pipeline design, implementation and control. Supply chain strategies must be contingent on market conditions. An important gap highlighted by this review is that is that the pipeline has not been researched in the ETO sector.

Synthesising the research gaps within the construction and pipeline management litertaure the following can be articulated. Research in construction supply chains is still in its infancy, and most of the supply chain research that has been conducted addresses the client-main contractor relationship rather than relationships with upstream suppliers. While pipeline management research, focusing on improving processes between order placement and delivery, has been insightful, most of the research has focused on high volume stable manufacturing supply chains.

Research question 2 can be formulated as:

Research Question 3: How can organisations improve pipelines in ETO construction supply chains?

2.11.2 Project uncertainty

Part 1 of the literature review identified the project environment as a distinguishing feature of ETO supply chains. This was reconfirmed in the structured literature review in part 2. Consequently, the discussion on supply chain uncertainty would not be complete without reference to the project management literature relating to project uncertainty. Project heterogeneity is well documented in the literature. Differences such as location and the amount of projects within an overall programme (Evaristo and van Fenema, 1999) and the amount of technological uncertainty (Shenhar and Dvir, 1996) have been described in the literature. As a result of this heterogeneity, and the uncertainty and risks that arise from it, project risk has attracted a large amount of attention from practitioners and researchers.

Edwards and Bowen (1998) presented an analytical review of construction risk literature from 1960 to 1997 and find over 280 papers relating to risk and risk management in authoritative English language publications. A considerable amount of published material relating to project risk analysis and assessment is available (Ackermann et al., 2007; Chapman, 1997; Mulholland and Christian, 1999; Mustafa and Al-Bahar, 1991) and risk management has also been a popular area for researchers (Al-Bahar and Crandall, 1990; Chapman, 1997; Conroy and Soltan, 1998). Much of the risk management literature seeks to establish formal risk management processes, protocols and management tools and techniques.

Project uncertainty has received much less attention in the literature. Ward and Chapman (2003) argued that the restricted focus of risk management must be modified to incorporate an uncertainty management perspective. Perminova et al. (2008) developed definitions of uncertainty for project management scholars and define it as "a context for risks as events having a negative impact on the project's outcomes or opportunities" (Perminova et al., 2008). DeMeyer et al. (2002) presented a useful classification of project uncertainty defining four types. Variation, they argue, refers to uncertainties where performance levels vary randomly but within a predictable range. Foreseen uncertainty refers to situations where a few known factors will influence the project but in unpredictable ways. Unforeseen uncertainty is where one or more major influence factors cannot be predicted and chaos refers to unforeseen events that completely invalidate the project's target, planning and approach.

2.12 SUPPLY CHAIN FLEXIBILITY

2.12.1 What is flexibility?

Flexibility is defined by the Collins dictionary as the ability to be "bent easily without breaking; pliable". Flexibility in the operations management literature is generally perceived as an adaptive response to environmental uncertainty (Gerwin, 1993). More specifically, it is a reflection of the ability of a system to change or react with little penalty in time, effort, cost or performance (Morlok and Chang, 2004; Upton, 1994). Hence, flexibility may be seen as a proactive attribute designed into a system, rather than a reactive behaviour that may in fact result in a detriment to time, effort, cost and performance (Naim et al., 2006). This echoes Gerwin's (1993) contrasting of a flexible factory, which quickly adapts to realised uncertainty, and proactive flexibility, which controls uncertainty through advance planning.

Slack (2005) found that managers accept that the word flexibility is used in two senses, to mean range and response. Range refers to the range of states or behaviours that a system can exhibit, whereas response refers to the ease with which the system moves from one state to another. A system which moves quickly, smoothly and cheaply between a range of states is considered as flexible. Flexibility may also be seen as having two distinct elements, those internal to the business that describe system behaviour, and those that are viewed externally by customers, which determine the actual or perceived performance of the company (Oke, 2005).

2.12.2 Why is flexibility important?

Flexibility is an effective response to uncertainty

The relationship between uncertainty and flexibility is well documented. Gerwin (1993) and Schmenner and Tatikonda (2005) proposed that uncertainties are the impetus for a manufacturing organisation to possess various flexibility types. Tang and Tomlin (2008) examine the benefits of different flexibility strategies in the context of supply chain risk management. They provided analytical models to illustrate the power of flexibility for reducing supply chain risk. Swamidass and Newell (1987), using an analytical path method and an empirical study of 35 manufacturing firms, confirmed that the greater the level of flexibility, the greater a firm's performance was. They also found that an organisation may find at least some help in coping with the high uncertainties imposed by their environment by increasing manufacturing flexibility. The relationship between uncertainty and flexibility has also been researched by Prater et al. (2001), Childerhouse and Towill (2004) and Vickery et al. (1999). These studies all suggested that flexibility is an effective response to uncertainty.

Flexibility is a source of competitive advantage

The turbulence of the modern business environment is well documented (Christopher, 2005). Globalisation, technological change and more demanding customers, amongst other drivers, result in higher levels of uncertainty for organisations. As customers demand faster response times and a wider variety of products, flexibility, above all other measures of manufacturing performance, is cited as a solution (Slack, 2005). Dreyer et al. (2004) , in a statistical analysis of the performance of 35 fish processing firms, conclude that flexibility is a valuable skill that has a major impact on competitive position. A seminal work by Hitt et al. (1998) argued that the most important attribute that firms must achieve to operate effectively in the modern competitive landscape is that of strategic flexibility. This was supported by Sanchez (1995), who concludes that in dynamic product markets relative competitive advantage may be explained largely by firms' differing strategic flexibilities.

Flexibility is an enabler of agility

Agile supply chains have been promoted as a route to competitive advantage in modern markets with flexibility as a key enabler to cope with high levels of uncertainty (Christopher, 2000; Naylor et al., 1999; Prater et al., 2001; Yusuf et al., 1999). Manufacturing flexibility has been well addressed in the literature (Gerwin, 1993; Koste and Malhotra, 1999; Oke, 2005; Upton, 1994, 1995), but flexibility in the larger context of supply chain flexibility has received less attention by researchers. As Oke (2005) has noted, the subject of flexibility can be complex and confusing. The plethora of research on flexibility has resulted in many perspectives and definitions. Ambiguity regarding terminology still exists, although the fundamental ideas appear to be very similar (Naim et al., 2006).

Agility has been proposed as a response to the high levels of complexity and uncertainty in modern markets (Christopher and Jüttner, 2000; Gunasekaran, 1999; Yusuf et al., 1999). According to Naylor et al. (1999), "agility means using market knowledge and a virtual corporation to exploit profitable opportunities in a volatile market place". The link between agility and flexibility is widely discussed in the literature (Christopher, 2000; Prater et al., 2001; Swafford et al., 2006). Swafford et al. (2006) propose that the combined effect of different types of flexibilities determine an organisation's supply chain agility, with flexibility being an antecedent of agility. Christopher (2000) suggested that the origins of agility lie in flexible manufacturing systems.

2.12.3 The development of a model for supply chain flexibility

From manufacturing to supply chain flexibility

Early studies of flexibility focused on the value of flexible manufacturing systems, establishing the importance of flexibility as a manufacturing capability, and attempting to define it (Collins and Schmenner, 1993; Gerwin, 1993; Slack, 2005; Upton, 1994). This has been followed by a number of papers seeking to establish more detailed definitions of flexibility types and dimensions (D'Souza and Williams, 2000; Koste and Malhotra, 1999; Koste et al., 2004; Oke, 2005; Vokurka and O'Leary-Kelly, 2000; Zhang et al., 2003). More recently, the flexibility debate has refocused towards supply chain flexibility, suggesting that manufacturing is too narrow in its scope and that flexibility must be conceived in the broader context of the supply chain (Duclos et al., 2003; Pujawan, 2004; Sanchez and Perez, 2005; Swafford et al., 2006; Vickery et al., 1999). However, the supply chain flexibility field is still at an early stage, and consensus regarding definitions, scope, meaning and application has not yet been achieved.

Vickery et al. (1999) defined supply chain flexibility as an amalgamation of product flexibility, volume flexibility, new product flexibility, distribution flexibility and responsiveness flexibility. Swafford et al. (2006) built on this and develop a model that explores the interactions among flexibilities with respect to design, sourcing, manufacturing and logistics. Prater et al. (2001) identified speed and flexibility of sourcing, manufacturing and delivery as key determinants of supply chain flexibility. Tachizawa and Thomsen (2007) concluded that there are two main strategies that could be employed at supply chain level in order to increase the flexibility of a supply chain: improved supplier responsiveness and flexible sourcing.

In summary, much of the flexibility research relates to manufacturing. There is a recognition that the scope needs to be widened to consider the flexibility of the supply chain, but research is still at an early stage of development with very little empirical testing. For this thesis it is important to note that supply chain flexibility has not been investigated in the ETO construction sector. At this point Research Question 4 is introduced:

Research Question 4: How can flexibility be rationalised in ETO construction supply chains?

Rationalisation of supply chain flexibility

Whilst the focus of flexibility is shifting from manufacturing to the wider supply chain, there is, as yet, little consensus on the definitions and concepts related to supply chain flexibility. The distinction between internal flexibilities, those internal to the business that describe system behaviour, and external flexibilities, which are viewed externally by customers, has already been noted (Oke, 2005). This section seeks to rationalise the internal and external flexibility types that determine supply chain flexibility.

External flexibility types for manufacturing are well documented in the literature (Oke, 2005). These have been synthesised by Naim et al. (2006), for both manufacturing and logistics flexibility. The following flexibility types, which are proposed as the external flexibility types of a supply system, are adapted from Naim et al. (2006) and can be defined as:

- New product flexibility is the range of, and ability to, accommodate the production of new product;
- Mix flexibility is the range and ability to change products currently being produced;
- Volume flexibility refers to the range of, and ability to, accommodate change in production output;
- Delivery flexibility is the range of, and ability to, change delivery dates;
- Access flexibility is the ability to provide extensive coverage, and reflects the capability of a supply chain to provide the required geographical coverage for different customers.

Internal flexibility types have been determined by a classification of literature. The classification of the supply chain flexibility literature can be found in table 2.11. It shows two key internal flexibility types which are termed antecedents of supply chain flexibility: vendor and sourcing flexibility. It is proposed that these two antecedents determine the external flexibilities of a supply system, those that are visible to the customer. Vendor flexibility consists of flexibilities related to manufacturing, warehousing and logistics. Sourcing flexibility consists of the ability of the network co-ordinator to reconfigure the supply chain, the ability to adapt to market requirements, ability to increase supplier responsiveness and the ability of the network co-ordinator to integrate the supply chain.

Using the literature, the antecedents of vendor and sourcing flexibility are developed over the following 2 sections. The following definitions are proposed:

1. Vendor flexibility - the specific types of flexibility relating to individual vendors that support manufacturing, warehousing or transport operations.
2. Sourcing flexibility - the ability to reconfigure a supply chain network through selection and de-selection of vendors.

A conceptual model for supply chain flexibility is shown in figure 2.4. It shows the 5 external flexibility types adapted from Naim et al. (2006) and the two antecedents of supply chain flexibility developed from the classification in table 2.11.

Authors	Vendor Flexibility			Sourcing Flexibility			
	Manufacturing	Warehousing	Logistics	Ability to Reconfigure the Supply Chain	Ability to Adapt to Market Requirements	Ability to Increase Supplier Responsiveness	Ability to Integrate the Supply Chain
(Abrahamsson et al., 2003)		X	X		X		
(Baker, 2006)		X			X		
(Das and Abdel-Malek, 2003)	X					X	
(Duclos et al., 2003)			X	X	X		
(Gerwin, 1993)	X						
(Lee, 2004)					X		X
(Lummus, 2005)	X		X				X
(Naim et al., 2006)			X				
(Prater et al., 2001)	X		X	X			
(Pujawan, 2004)	X	X	X				
(Slack, 2005)	X						
(Stevenson and Spring, 2007)				X			X
(Stevenson and Spring, 2009)				X		X	X
(Swafford et al., 2006)	X	X	X		X		
(Swafford et al., 2008)							X
(Tachizawa et al., 2007)				X		X	
(Tachizawa and Gimenez, 2009)				X		X	X
(Vickery et al., 1999)	X				X		
(Zhang et al., 2002)	X		X				X
Total	9	4	8	6	6	4	7

Table 2.11: Classification of supply chain flexibility literature

Vendor Flexibility

Vendor flexibility refers to the collective types of flexibilities offered by different vendors in the supply chain. Vendor flexibility may be one or a combination of manufacturing, warehousing and transport flexibilities. In a review of empirical research on manufacturing flexibility, Vokurka and O'Leary-Kelly (2000) highlighted 15 dimensions of manufacturing flexibility, most of them similar to those identified earlier by Koste and Malhotra (1999). Amongst others, flexibility types and measurements have also been investigated by Slack (2005), Gerwin (1993), Zhang et al. (2003) and Koste and Malhotra (2004). These have been summarised by Naim et al. (2006) as either internal flexibility types, machine, process, operation, capacity and re-routing flexibility, or external flexibility types, product, mix, volume, delivery and access flexibility.

Warehousing flexibility has also been discussed in the literature. This would include the ability of a system to cope with variable inventory volumes (Baker, 2006), time window pressure (Abrahamsson et al., 2003; Barad and Even Sapir, 2003) and to offer additional value-adding services such as different forms of palletisation, packaging and cross-docking (Abrahamsson et al., 2003; Baker, 2006). Synthesising the literature on transport flexibility, Naim et al. (2006) identified key components of transport flexibility. Nine internal flexibility types are offered. The first three, mode, fleet and vehicle flexibility, relate to the physical movement of the goods. Node, link and temporal flexibility are more closely aligned with the infrastructure provision. The final three internal flexibility types are capacity, routing and communication flexibility. The external flexibility types for a transport system are the same as those defined in the previous section.

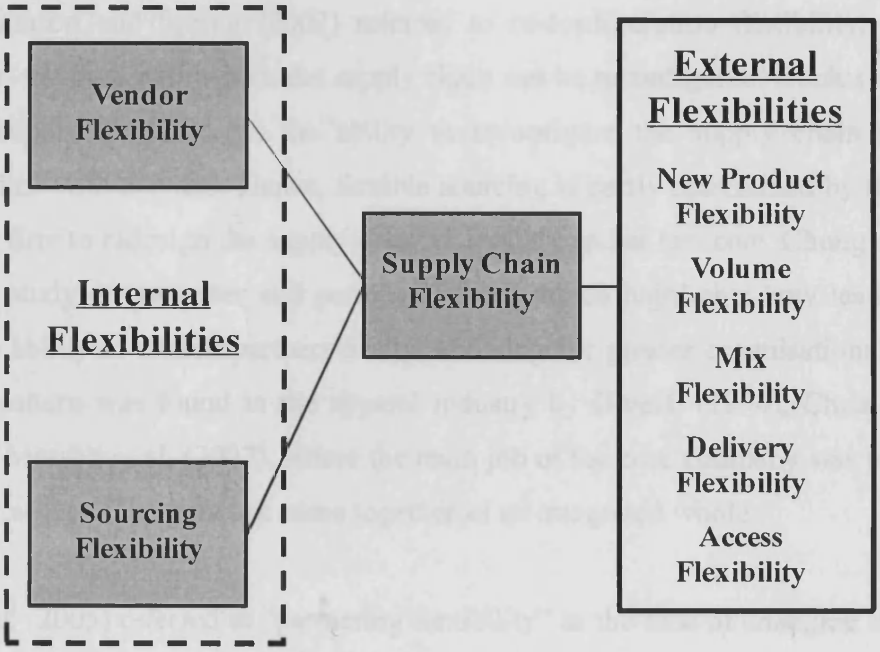


Figure 2.4: Conceptualisation of supply chain flexibility

At a supply chain level, Das and Abdel-Malek (2003) define flexibility as the "elasticity" of the buyer-supplier relationship under changing supply conditions. They suggest that order quantities and supply lead times are the two most common changes in supply chains. Gosain et al. (2005) used "offering flexibility" to describe an important feature of supply chain flexibility: the ability of a supply chain linkage to support changes in product or service offering, in response to changes in the business environment. However, Swafford et al. (2006) highlighted that such definitions of supply chain flexibility primarily focus on the existing supply chain structure and have a narrow view of supply chain flexibility, consistent with the idea of rigid flexibility (Collins and Schmenner, 1993). Stevenson and Spring (2007) built on this, and argue that rigid flexibility, which is bounded by existing relationships and existing supply chain structures, provides limited scope for flexibility in the supply chain.

Sourcing Flexibility

An important component of sourcing flexibility is the ability to reconfigure the supply chain. Tachizawa and Thomsen (2007) considered that flexible sourcing should involve the adoption of a larger supplier base and constantly redesigning and reconfiguring the supply chain. Stevenson and Spring (2007) referred to re-configuration flexibility, which they described as the ease with which the supply chain can be reconfigured. Duclos et al. (2003) described supply flexibility as the ability to reconfigure the supply chain altering the product in line with demand. Hence, flexible sourcing is partly determined by the ability of the leading firm to redesign the supply network quickly and at low cost. Chung et al. (2004) provided a study of computer and peripheral firms which highlights how lead companies rely on the ability to switch partners easily, allowing for greater organisational flexibility. The same pattern was found in the apparel industry by Gereffi (1994), Christopher et al. (2004) and Masson et al. (2007), where the main job of the core company was to make sure that all the pieces of the network come together as an integrated whole.

Gosain et al. (2005) referred to "partnering flexibility" as the ease of changing supply chain partners in response to changes in the business environment. This definition highlights the role of long term relationships in developing supply chain flexibility. There are a range of collaborative arrangements, which can be competitive (Cousins, 2002) and network types, which should be configured based on the nature of product that they are created for (Lamming et al., 2000). However, it is possible that long term relationships could result in the "rigid flexibility" described by Stevenson and Spring (2007) or a "lock-in" effect, whereby high levels of asset specificity and investment reinforce continuity of the relationship (Wathne and Heide, 2004).

Another important element of sourcing flexible is adaptability. An adaptable supply chain is one that can adjust its own supply chain design to meet structural shifts in markets, and modify supply networks to strategies, products and technologies (Easton and Rothschild, 1987; Lee, 2004). Lee (2004) defined the objective of an adaptable supply chain as adjusting supply chain design to accommodate market changes. Duclos et al. (2003) included market flexibility in their classification, which they defined as the ability to mass customise, and build close relationships with customers, including designing and modifying new and existing products. Vickery et al. (1999) referred to this as responsiveness to target markets.

Sourcing flexibility may also involve a buying organisation increasing the responsiveness of suppliers. Increasing responsiveness is used to describe practices by a buying organisation to increase supplier response capabilities, such as suppliers' short term process flexibility (Tachizawa and Thomsen, 2007). This may represent an attempt to improve the overall vendor flexibility of a supply system or the specific parts of the system, such as manufacturing flexibility. Das and Abdel-Malek (2003) highlighted the need to estimate the flexibility of potential supply chain partners and make a choice accordingly. A final consideration for flexible sourcing is supply chain integration. Christopher (2000) has emphasized the role of integrating the virtual supply chain in developing agility, and Swafford et al. (2006) found that higher levels of agility can be achieved by integrating information flows through a value chain. Lee (2004) referred to the importance of alignment between different supply chain members to improve the performance of the entire chain. Once a supply chain is reconfigured for a specific purpose it must then be integrated to ensure that it performs effectively.

2.12.4 Supply chain flexibility and purchasing

A range of portfolio models have been proposed in the literature in order to support purchasing decisions and supplier selection. Kraljic's (1983) seminal paper on purchasing strategy classifies purchases according to a four box portfolio analysis model. The dimensions of the four box model are segmented by "importance of purchasing" and "complexity of supply market". A four by four matrix is then used to determine four categories of supplier including "strategic" (high profit impact, high supply risk), "bottleneck" (low profit impact, high supply risk), "leverage" (high profit impact, low supply risk) and "non critical" (low profit impact, low supply risk). Individual plans are then offered for each category of supplier.

Olsen and Ellram (1997) built on Kraljic's portfolio model. They argued that supplier relationships can be categorised based on the relative supplier attractiveness and the strength of the relationship between the buyer and supplier, and propose more detailed guidelines for the factors influencing supplier attractiveness and strength of relationship. A three by three model was developed. De Boer et al. (2001) also proposed a classification to describe the diversity of purchasing situations. They plotted present day purchasing practice of new task, modified rebuy (leverage items), straight rebuy (routine items) and straight rebuy (strategic/bottleneck) against different phases in the supplier selection process: problem definition, formulation of criteria, qualification and choice. The implications for the different phases are then explored for each situation.

More specifically to the construction sector, Cox (2009) explored the most appropriate way in which construction goods and services can be purchased. A two by two matrix with 'level of work and scope' with a supplier (either just working with a first tier supplier or becoming more deeply involved with different tiers of the supply chain) on one axis and 'focus of buyer relationship' with supplier on the other (either reactive, keeping suppliers at arms length, or proactive, becoming proactively involved with suppliers operations) is developed. The interactions between these variables result in four options for buyers in construction: supplier development, supply chain sourcing, supplier development and supply chain management. These categories of suppliers are then developed further to take account of power and leverage circumstances and appropriate relationship management strategies.

Synthesising the literature, a number of dimensions of purchasing are identified as important for project purchasing. It is important to highlight these criteria as they are used later in this thesis for the development of a purchasing model. An important gap that is not considered in the purchasing literature is the role of supply chain flexibility in purchasing decisions. The purchasing criteria from the literature are as follows:

- Criticality – The criticality of the output of a supplier or subcontractor to project success. Some products or services will have significant implications for cost and time if they fail (Constructing-Excellence, 2003);
- Regularity of demand – The extent to which demand is one off or project specific or high volume, and applies to a number of different projects (Ireland, 2004);
- Spend – This is used this to refer to the proportion of total procurement or relative cost spend that a service, supplier or subcontractor accounts for (Constructing-Excellence, 2003);
- Degree of supplier involvement and development – This refers to the extent to which the buying organization proactively develops supplier capabilities and collaborative relationships (Cox, 2009);
- Supply Risk – This refers to the extent of monopoly or oligopoly conditions, entry barriers, the pace of technological advance and complexity of the products (Kraljic, 1983).

2.13 CONFIRMING THE LITERATURE GAPS IN RELATION TO ETO CONSTRUCTION SUPPLY CHAINS

This review highlights that, overall, ETO supply chains have received very little attention in the literature. Uncertainty and flexibility have also not been researched in the context of ETO Construction supply chains. Based on all elements of the literature review, the gaps in the existing research that will be further investigated in this thesis can be defined as follows:

- While it has been acknowledged that different types of supply chains are associated with different uncertainty profiles, the supply chain uncertainty literature has not addressed the particular sources of uncertainty related to the ETO construction supply chains. Furthermore, the supply chain uncertainty circle has been successfully applied in a range of sectors, but there are no applications in the construction sector.

- Research in construction supply chains is still in its infancy. Most of the supply chain research that has been conducted addresses the client-main contractor relationship rather than relationships with upstream suppliers. While pipeline management research, focusing on improving processes between order placement and delivery, has been insightful, most of the research has focused on high volume stable manufacturing supply chains.
- Much of the flexibility research relates to manufacturing. There is a recognition that the scope needs to be widened to consider the flexibility of the supply chain, but research is still at an early stage of development with very little empirical testing. For this thesis it is important to note that supply chain flexibility has not been investigated in the ETO construction sector. The role of supply chain flexibility has also not been considered in purchasing classifications.
- Bodies of knowledge on uncertainty, flexibility and pipeline management have not been integrated for the specific needs of the ETO construction sector.

2.14 SUMMARY

This chapter has reviewed the literature relevant to ETO supply chains. The ETO supply chain is framed by reference to a taxonomy of six supply chain structures, where the ETO supply chain has the highest levels of customisation compared to the other structures. The literature relating to construction supply chains was reviewed and place in the context of the ETO supply chain.

A structured literature review of the ETO supply chain concludes that an ETO supply chain operates in a project environment and that each product is different to the last. Production dimensions of the supply chain are completely customised and the decoupling point is located at the design stage. However, the design dimension may have standard elements: existing designs maybe modified to order or completely new designs may be developed to order. There may also be sector specific differences in which certain activities in the supply chain may be standardised. The structured literature review provides a framework to understand the developments that have emerged in the ETO field, as well as providing a theoretical grounding for this thesis. This part of the literature review concludes that there is a need to tailor strategies to the ETO supply chain, that there is no consensus on the role of flexibility in ETO supply chains.

The final part of the review addresses the literature surrounding supply chain uncertainty and supply chain flexibility. In particular the supply chain uncertainty literature raises the supply chain uncertainty circle as a framework for considering uncertainty. This is important as the model is applied to ETO uncertainties in chapter 5. A conceptual model of supply chain flexibility was also developed. This is used in chapter 7 to investigate supply chain flexibility in the construction case studies. In the last section of the literature review the literature gaps are summarised. As a result of the literature review section, four research questions have been developed. In the next chapter these research questions are discussed with reference to research methods and the overall methodology.

SUMMARY OF CHAPTER 2 AIMS

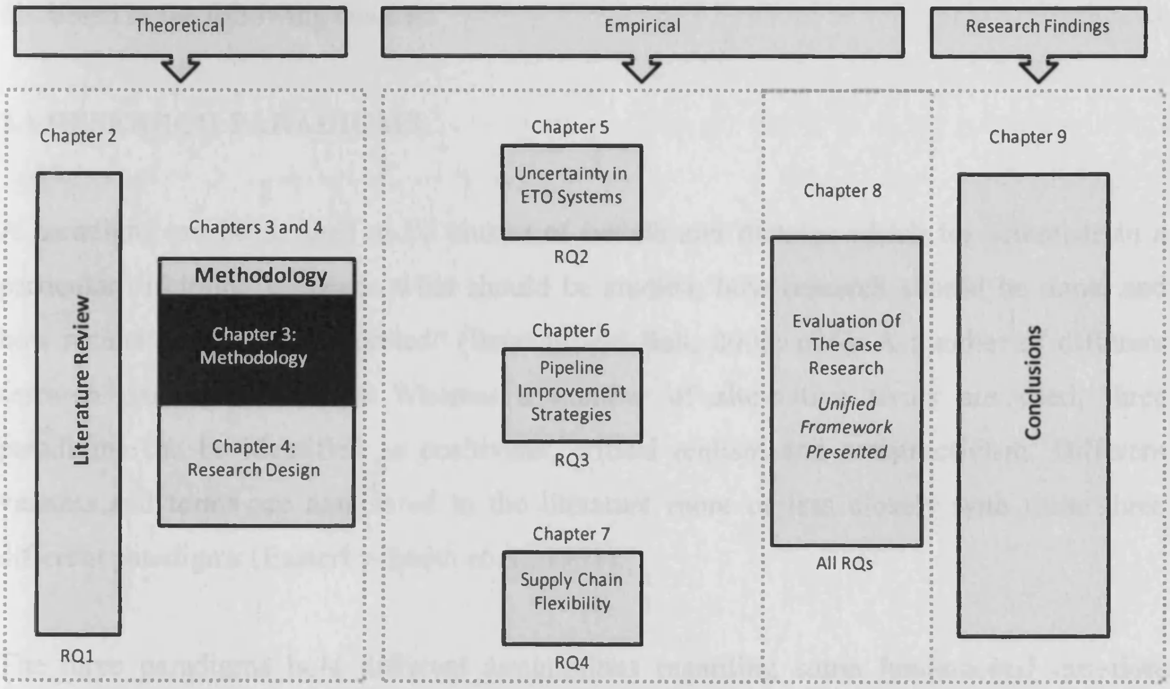
1. **Develop a foundation for the thesis in the published literature**
   - Important areas of literature have been reviewed to develop a foundation including literature relating to construction supply chains, supply chain structures, the ETO supply chain, supply chain uncertainty and supply chain flexibility.
2. **Formulate research questions in relation to the literature and identify the research gaps**
   - Four research questions have been developed from the literature.
   - The gaps in the different bodies of knowledge are identified at the end of the chapter
3. **Compare the engineer-to-order supply chain with other types of supply chains**
   - A taxonomy of supply chain structures was developed, and the ETO supply chain is compared with the characteristics of 5 other supply chain structures: MTO, BTO, ATO, MTS and STS.
4. **Identify the characteristics of the engineer-to-order supply chain**
   - A robust definition of the ETO supply chain has been developed
5. **Develop a conceptual model to rationalise supply chain flexibility**
   - Supply chain flexibility has been rationalised using antecedents of sourcing and vendor flexibility and 5 external flexibility types

CHAPTER 3

METHODOLOGY

CHAPTER 3 AIMS

1.Review research philosophy literature and explicate the philosophical position adopted
2.Critically review research methods that will be used in the study
3.Justify multiple case study research and mixed methods design



3. INTRODUCTION

This chapter begins by describing three major research paradigms. This is followed by the identification of the paradigmatic stance adopted. The research questions that were developed from the literature in chapter 2 are then revisited. They are linked to different areas of theory, and the nature of investigation for each of the research questions is summarised. The research strategy, namely multiple case study research, is discussed in terms of strengths and weaknesses, and a justification of the research strategy selection is offered. The strengths and weaknesses of specific data collection techniques and data analysis techniques are assessed. The application of these specific techniques in the thesis is discussed in the following chapter.

3.1 RESEARCH PARADIGMS

A paradigm can be defined as "a cluster of beliefs and dictates which for scientists in a particular discipline influence what should be studied, how research should be done, and how results should be interpreted" (Bryman and Bell, 2003: p25). A number of different research paradigms coexist. Whereas a number of alternative terms are used, three paradigms can be identified as positivism, critical realism and constructivism. Different variants and terms are associated in the literature more or less closely with these three different paradigms (Easterby-Smith et al., 1991).

The three paradigms hold different assumptions regarding some fundamental questions relating to the pursuit of knowledge. Before the three paradigms are explored in greater depth mention must be made of some of the terms associated with these assumptions. Ontology refers to the nature of reality. Two aspects of ontology are objectivism and subjectivism. Objectivism holds that social entities exist in reality external to social actors concerned with their existence. Subjectivism holds that social phenomena are created from the perceptions and consequent actions of those social actors concerned with their existence (Saunders et al., 2007). Epistemology concerns the general set of assumptions about the best ways of inquiring into the nature of the world (Easterby-Smith et al., 1991). It refers to the question of what is, or should be, regarded as acceptable knowledge in a discipline (Bryman and Bell, 2003). Finally, axiology refers to the role of values in research (Goles and Hirschheim, 2000). This relates to the extent to which research is viewed as value free and unbiased or value laden and biased.

3.1.1 Positivism

Positivism draws much from scientific experimentation where knowledge is extended by objective observation and measurement. The important, or most widely accepted, components of positivism are outlined in table 3.1. The ontological assumption in positivism is that there is an external world independent of researcher. The epistemological assumption is that this external world can be observed objectively. There is a hypothetico-deductive cycle of enquiry which suggests that science proceeds through a process of hypothesizing fundamental laws and then deducing what kind of observations will demonstrate the truth or falsity of these hypotheses (Easterby-Smith et al., 1991). Since only knowledge that is observed objectively is considered valid, the axiology is value free (Wass and Wells, 1994). Typically, a hypothesis about a specific causal relationship between a theoretically dependent object and a set of theoretically independent objects is deduced from abstract theoretical concepts. A hypothesis is then expressed, which is then refuted or verified.

Research Paradigm	Positivism	Critical Realist	Constructivist
Ontology	Objectivism - a world exists independent of subjective consciousness	1) A real world exists independent of subjective consciousness 2) Stratification of ontology	Subjectivism - the real world does not exist outside the consciousness of the individual, Realities are multiple and constructed.
Epistemology	Only that which is objectively observed is valid knowledge	Valid knowledge comprises individual comprehension of the external world	Valid knowledge comprises individual comprehension of the external world
Axiology	Value free	Value bound	Value bound
Objective	Uncover general laws, discovery	exposure	Uncover and explain individual conceptualisation and interpretation of external factors, invention
Type of Data (tendency)	Quantitative	Quantitative & Qualitative	Qualitative
Techniques for Collecting Data	Simulation, Mathematical Modelling, Structured Questionnaire	Complete tool kit often in context of a case study	Observation, Interviews, Textual Analysis, Ethnography
Cycle of Enquiry	Hypothetico-deductive	Retroductive	Inductive – theory grounded in empirical observation
System Assumptions	Closed	Open	Open
Associated Terms	Scientific method, Natural Science,	Pragmatism	Phenominalism, antipositivist, naturalism, constructiionism, constructivism, hermeneutic, relativism, interpretivism see p24 easterby
Sources: (Bertrand and Fransoo, 2002; Bryman and Bell, 2003; Easterby-Smith et al., 2008; Easterby-Smith et al., 1991; Eriksson and Kovalainen, 2008; Saunders et al., 2007; Wass and Wells, 1994)			

Table 3.1: Characteristics of research paradigms

Positivism inclines towards quantitative data, and includes research methods such as simulation, mathematical modelling, and structured questionnaires (Bertrand and Fransoo, 2002; Bryman and Bell, 2003; Easterby-Smith et al., 1991; Wass and Wells, 1994). The main strengths of positivism and the associated methodologies are that they can provide coverage of a range of situations, they can be fast and economical, and they can have considerable relevance to policy decisions. The weaknesses are that they are rather inflexible and artificial. They are not very effective in understanding processes or the significance that people attach to actions, and the implications for actions are not obvious (Easterby-Smith et al., 2008). A key weakness of positivism, and the associated research methods, is well summarised by Bertrand and Fransoo (2002) who argue that it "does not (yet) provide us with sufficiently powerful methods of analysis to address problems that come close to the complexity that is observed in most real life operational processes" (Bertrand and Fransoo, 2002: p261). This difficulty is reflected in the assumption of a closed system. Models require clear boundaries and assumptions in order to model the change of one variable upon another.

3.1.2 Constructivism

A new paradigm has arisen during the last half century largely in reaction to the application of positivism to the social sciences. At the centre of this paradigm is that all knowledge is socially dependent because all knowledge is socially constructed (Boghossian, 2006). The knower and the known are interactive and inseparable, whereas in positivism the knower and known are independent (Lincoln and Guba, 1985). The interpretivist paradigm holds that the world is socially constructed and the logic of scientific experimentation is rejected as a model to conduct social research. The ontological assumption rejects the independence of the social world from subjective interpretation and argues that the real world does not exist outside the consciousness of the individual. In epistemological terms, valid knowledge comprises individual comprehension of the external world. Research is value bound and the aim of research is to uncover and explain individual conceptualisation and interpretation (Wass and Wells, 1994).

Constructivism primarily relies on inductive reasoning, where data is collected first and then theory developed as a result of data analysis (Saunders et al., 2007). Constructivism also inclines towards qualitative methods such as observation, interviews, textual analysis and ethnography (Bryman and Bell, 2003; Wass and Wells, 1994). The strengths of constructivism and the associated methodologies are that they provide the ability to look at change processes over time, to understand people's meaning and to adjust to new issues and ideas as they emerge. It also provides the ability to contribute to the evolution of new theories and an approach to gathering data which can be described as natural rather than artificial (Easterby-Smith et al., 2008). Opposition to the constructivist position is well summarised by Boghossian (2006), who suggests that while the constructivist position is appealing as it is empowering, "the intuitive view is that there is a way things are that is independent of human opinion, and that we are capable of arriving at belief about how things are that is objectively reasonable, binding on anyone capable of appreciating the relevant evidence regardless of their social or cultural perspective" (Boghossian, 2006: p131).

3.1.3 Critical realism

Critical realism offers an alternative position to constructivism and positivism. It proposes a way of combining positivist conceptions of an external world with the recognition of interpretive understanding that is a feature of constructivism. Critical realism accepts that an entity can exist independently of our knowledge of it, but the possibility of subjective interpretation of the world and the impact of meaningful interpretation on action are recognised (Wass and Wells, 1994). The critical realist perspective argues for a stratified ontology, which distinguishes between the real, the actual and the empirical (Bhaskar, 2008). The real is whatever exists, and is the realm of objects, structures and powers. These powers may exist unexercised. The actual refers to causal powers that are activated. Finally, the empirical refers to the events that we actually experience.

Critical realism accepts that an entity can exist independently of our knowledge of it. However, the possibility of subjective interpretation of the world and the impact of meaningful interpretation on action are recognised. The world can only be known in terms of available descriptions or discourses. Events are affected by underlying structures and mechanisms, which interplay with different contexts. A fundamental aim of critical realism is to uncover these different levels or layers of social reality and construct models of underlying or generative structures, explaining the make-up of mechanisms or structures and their effects under certain conditions. From this perspective the objective of a social science project is to demonstrate explanatory mechanisms which link a diverse empirical reality via an intervening contextual layer to deeper social structures (Bryman and Bell, 2003; Collier, 1994; Wass and Wells, 1994).

One of the most distinctive features of critical realism is its analysis of causation. Positivism draws heavily on the successionist view of regularities among sequences of events. From the critical realist perspective, causation is not understood on the model of regular successions of events; therefore explanation need not depend on finding regularities or searching for putative social laws. What causes something to happen has nothing to do with the amount of times we have observed it happening. Explanation, from a critical realist perspective, focuses on identifying causal mechanisms, discovering how they work, and discovering if they have been activated in different conditions (Sayer, 1999). Consistent regularities are only likely to occur under special conditions. In a closed system causal powers are stable and the external conditions are constant. This rarely occurs spontaneously in the social world, which is much more likely to be characterised by open systems, where the same causal power can produce different outcomes under different conditions (Bhaskar, 2008).

3.1.4 Research in supply chain and operations management

The positivist paradigm has been dominant in both operations management and supply chain management. As a result, much of the early research in operations management has been confined to quantitative modelling and statistical analysis (Meredith et al., 1989). Within the field of operations management there have been calls to balance the traditional rationalist methods of optimisation, simulation and statistical modelling with empirical studies that gather data from the field in different ways (Flynn et al., 1990; Meredith, 1998). Scudder and Hill (1998) highlighted that empirical research in operations management has demonstrated a bias towards survey and statistical research methods. They review papers from 1986 to 1995 published in 13 different journals and find that out of the empirical research available 294 papers utilised survey methods, 168 used case studies, 10 used database (archival analysis) and 5 used panel studies (group of experts). In the field of supply chain management, Burgess et al. (2006) find that out of 100 randomly selected journal articles, taken from July 2003 onwards, 39 were conceptual analytical, 7 were mathematical analytical, 23 used statistical sampling techniques and 31 used case studies. Burgess et al. (2006) concluded from their sample that a positivist research paradigm stance is prevalent.

3.1.5 The paradigmatic stance adopted in the thesis

The position adopted in this research is that of critical realism. The stratified ontology assumed by critical realism offers an appealing position from which to investigate the layers of uncertainty and the key characteristics of the particular context, the ETO supply chain. In terms of epistemology, the critical realism position acknowledges the subjective role of the researcher in generating knowledge. The argument adopted herein is that claims of a researcher's independence in the social sciences are hard to sustain and that the value free, objective, detached observation associated with positivism is difficult to achieve. Subjectivity, therefore, need not be seen as a failing needing to be eliminated but as an important element of the research process.

This research will incline towards retroductive logic of enquiry rather than the hypothetico-deductive reasoning often related with positivism. Research questions are modified as research iterates between observation and theory. It will also assume a critical realist view of causation with the ETO system being characterised as an open system. The ETO system is complex and it would be difficult to isolate out components and examine them under controlled conditions as suggested by the positivist tradition. The closed system approach linked with positivism would be too simplistic and constrained to achieve the rich and detailed characterisation of the system that this research aims to achieve.

The following summarises the key influences of critical realism on this thesis.

- *Stratification of ontology.* Supply chains can be thought of as having underlying mechanisms and structures that drive events.
- *Interpret 'truth' subjectively.* The researcher's role in generating knowledge is acknowledged as subjectivity is seen as part of the process. The role of opinions and interpretation are accepted as valid in the research process.
- *Research is not value free.* The argument adopted herein is that claims of a researcher's independence in the social sciences are hard to sustain and that the value free, objective, detached observation associated with positivism is difficult to achieve.
- *The ETO supply chain is an open system.* A supply chain can be viewed as an open system with mechanisms, powers and structures contributing to occurrences. Research can be designed with the aim of uncovering these structures and powers.
- *The critical realist view of causation.* It is more important to seek underlying, contextual mechanisms, powers and structures than repeated occurrences.
- *A retroductive cycle of enquiry.* Research can be investigated using a retroductive cycle of enquiry with iterations between theory and data. The researcher's role in generating knowledge is acknowledged, as subjectivity is seen as part of the process.
- *A range of methods are compatible within a case context.* Research methods often form a complete tool kit of techniques in the context of a case study. A range of research methods are appropriate, including both qualitative and quantitative approaches (Collier, 1994; Sayer, 1999; Wass and Wells, 1994).

3.2 RESEARCH QUESTIONS

Research questions 1-4 were developed from the literature in the last chapter. However, as noted by Eisenhardt (1989), the constructs, questions, definitions and measurements in case study research often emerge from the analysis process itself rather than being specified a priori. Emergent relationships between constructs are also confirmed, revised or disconfirmed as case study research progresses. Emergent concepts, questions and findings were compared with enfolding literature as the research progressed (Eisenhardt, 1989). Table 3.2 brings together research questions, showing how they relate to different areas of the literature and the nature of investigation. This builds on the preceding literature review chapter.

Research Question	Theory/Body of Knowledge	Nature of Investigation
(1) How do construction supply chains fit within a taxonomy of supply chain structures?	Supply chain structures, ETO Supply chain, Construction Supply Chains, Systems thinking	• Conceptual – places construction within a taxonomy of six supply chain structures • Structured literature review – synthesis of ETO literature allows construction to be placed within the broader ETO body of knowledge • Case studies and evaluation interviews are compared with ETO characteristics
(2) How can the sources of project uncertainty in Engineer-to-order construction supply chains be identified and categorised?	Supply chain uncertainty, Project risk and uncertainty	• Development of a five stage method to identify and classify uncertainty in ETO construction supply chains • Application of the five stage model to five construction projects – to demonstrate how the method may be applied to a group of projects • Six evaluation interviews - to establish accuracy and potential to generalise across the construction sector
(3) How can organisations improve pipelines in ETO construction supply chains?	Time-based competition, Systems dynamics, Supply chain collaboration	• Investigation of 12 supplier pipelines via a pipeline survey • Six evaluation interviews - to establish accuracy and potential to generalise across the construction sector
(4) How can flexibility be rationalised in ETO construction supply chains?	Supply chain flexibility, Purchasing Models	• Conceptual – develops a model of supply chain flexibility • Investigation of the conceptual model through all units of analysis: two network co-ordinators, 12 supplier pipelines and five projects. • Six evaluation interviews - to establish accuracy and potential to generalise across the construction sector

Table 3.2: Integration of research questions with theory

Research question 1 is grounded in the literature relating to supply chain structures, and the construction supply chain management literature. A taxonomy of supply chain structures was proposed in the literature review and definitions for the ETO supply chain were developed. This provides the theoretical grounding for comparing the characteristics of ETO supply chain with case studies and the evaluation interviews.

Research question 2 is primarily grounded in the supply chain uncertainty literature. It aims to uncover the specific uncertainties that can be found in the ETO construction supply chain. The project uncertainty and risk body of knowledge also contributed to the development of this research question. This is important, as a project environment is an important feature of the ETO supply chain structure. An existing conceptual model, the supply chain uncertainty circle, which has been applied in a number of industries and sectors, is applied to the ETO sector. This research question is primarily investigated using case studies of 5 projects from two ETO construction systems, using a risk and uncertainty protocol to collect data. This is also supported by the 6 evaluation interviews.

Research question 3 is grounded in a number of different bodies of knowledge. Systems dynamics emphasizes the importance of supply pipelines for the overall dynamics of a supply chain, and the time-based competition literature highlights the strategic significance of lead-time analysis and time compression in supply pipelines. The question is also linked to the supply chain collaboration literature, suggesting that individual organisations in a supply chain can work together to improve supply pipelines. Research question 3 is primarily investigated through 12 supplier pipelines from 2 ETO systems. Data is collected via a 'pipeline survey' protocol. This is supported by the 6 evaluation interviews.

Research question 4 is grounded in the literature relating to supply chain flexibility, within the context of agile supply chains. It also draws on purchasing literature that addresses criteria and models for supplier selection. Using the supply chain flexibility literature, a conceptual model for supply chain flexibility was developed in the literature review chapter (see section 2.13). A purchasing model is also developed during the investigation of research question 4. Case studies involving all units of analysis are used in answering the research question. Two network co-ordinators, the 12 supplier pipelines and 5 projects from the 2 ETO systems are used. This is supported by the 7 evaluation interviews.

3.3 RESEARCH APPROACH

3.3.1 The selection of a multiple case study methodology

Multiple case studies are used in this thesis. This section justifies and evaluates the approach adopted. Yin (2003) defined a case study as "an empirical enquiry that investigates a contemporary phenomenon within its real life context" (Yin, 2003: p12). Often, the boundaries between phenomenon and context are not clearly evident. According to Yin

(2003) the first and most important condition for selecting research designs is the type of research question being asked. Case research is particularly suitable for exploring 'why' and 'how' research questions. The research questions in this thesis are exploratory 'how' questions. Handfield and Melnyk (1998) linked research purpose, question and typical research method. They identify six different purposes: discovery, description, mapping, relationship building, theory validation, theory extension/refinement. The link between research, questions and methods in this thesis is summarised in table 3.3. It shows that multiple case studies are appropriate for the purposes of this study.

Purpose	Research Question in Thesis	Appropriate Research Methods
Description: explore territory	How do construction supply chains fit within a taxonomy of supply chain structures?	In depth case study (unfocused) Longitudinal case study
Mapping: indentify and describe critical variables	How can the sources of project uncertainty in Engineer-to-order construction supply chains be identified and categorised? How can organisations improve pipelines in ETO construction supply chains?	Focused case studies In depth field studies Multi site case studies Best in class case studies
Relationship building: identify linkages between variables, causal understanding	How can organisations improve pipelines in ETO construction supply chains? How can flexibility be rationalised in ETO construction supply chains?	Focused case studies In depth field studies Multi site case studies Best in class case studies

Table 3.3: The link between research purpose, questions and methods (source: adapted from Handfield and Melnyk, 1998)

Stuart et al. (2002) suggested that case studies are appropriate if there is a lack of well supported definitions or metrics for a particular research question or phenomenon. Benbasat et al. (1987) also indicated that case research is appropriate for those in which research and theory are at their early, formative stage, the variables are still unknown and the phenomena is not well understood. The focus of this thesis is the exploration and description of a particular type of system or supply chain which has hitherto been under-researched. Case studies, therefore, are also suitable considering the lack of maturity of the topic area. Only a small number of papers have focused purely on the development of the ETO supply chain and it is significantly under researched in comparison with MTS or ATO structures (Hicks et al., 2000, 2001). As a result, there is little consensus as to the definition of an ETO supply chain. It may be referred to as a 'project supply chain' (Elfving et al., 2005) or a 'one of a kind supply chain' (Hameri, 1997) or as 'design to-order' (Amaro et al., 1999) where definitions have very many overlaps. Many of the variables, concepts and subsystems are also poorly defined and understood. This would make it difficult to ground any large scale survey work within existing theory and calls for more exploratory, case based methods. This research helps to develop these definitions and concepts.

The case study is preferred when examining contemporary events, but when the relevant behaviours cannot be manipulated (Yin, 2003). A key advantage in using the case study approach to investigate the research questions outlined in this paper is the rich accounts and descriptions of a natural setting that are offered, and the ability to learn the innovations put in place by practitioners. Rich descriptions of context will help to highlight the peculiarities of the ETO system and the various subsystems within it. Supply chain management research has also been highlighted as being a particularly applied field. It is both for management and about management (Tranfield and Starkey, 1998). Knowledge production primarily moves forward by a constant flow back and forth between theoretical and applied (Gibbons et al., 1994). Case research strategy is well suited for capturing the knowledge of practitioners and developing theories from it. Case base research is also suitable for exploring which theories are relevant to the ETO sector. As noted by Stuart et al. (2002), case based research attempts to ground theoretical concepts with reality and find out the conditions under which theories are applicable.

Meredith (1998) cites three strengths of case research based on suggestions made by Benbensat et al. (1987):

- The phenomena can be studied in their natural setting and meaningful, relevant theory generated from understanding gained through observing actual practice;
- The case method allows the questions of why, what and how to be answered with a relatively full understanding of the nature and complexity of the complete phenomenon;
- The case method lends itself to early, exploratory investigations where the variables are still unknown and the phenomena not all understood.

A further strength of the case study data collection is the opportunity to many different sources of evidence to develop converging lines of enquiry (Yin, 2003). To get an accurate characterisation of the ETO supply chain, and the type of uncertainties that are experienced, a number of techniques are required. If a single method was used it would be likely that the conclusions would be overly biased towards a certain perspective. The weaknesses of adopting an approach that relies on triangulation includes the time and cost of the approach, the requirements that the researcher to be well versed in a range of data collection techniques and the danger of analysing different data types separately (non convergence) (Yin, 2003).

Yin (2003) argued that traditional prejudices against the case study approach are the historical lack of rigour in carrying out case research, the reduced basis for scientific generalisation and the time constraints involved in managing the scale of data involved in case research. Eisenhardt (1989) suggested that there is a danger that case study research can yield theory which is overly complex or that is narrow and idiosyncratic. Case research is also often associated with increased cost and time when compared with other research methods (Stake, 1994). The agendas of participating companies may also provide difficulties for qualitative case research. Companies may agree access and in kind support but may have a preferred outcome for the results of the study.

Another commonly perceived weakness of case research is the issue of generalisability. The extent to which case studies provide a basis for empirical generalisability is a common criticism of case studies (Gill and Johnson, 1997; Stake, 1994). Yin (2003) defends the case study approach against these criticisms by claiming that case studies are generalisable to theoretical propositions and analytic generalisations and do not seek to enumerate frequencies or claim statistical generalisation to populations.

3.3.2 The Selection of a Mixed Methods Design

The view adopted in this thesis is that qualitative and quantitative techniques should be viewed as complementary rather than as rivals. The use of different kinds of data allow for greater accuracy in research. Greene at al. (1989) reviewed 57 mixed methods studies from the 1980s and listed 5 purposes:

- triangulation, or seeking convergence of results;
- complementarity, or examining overlapping and different facets of a phenomena;
- initiation, or discovering paradoxes, contradictions, fresh perspectives;
- development, or using the methods sequentially, such that results from the first method inform the use of the second method;
- expansion, or mixed methods adding breadth and scope to a project.

Triangulation is broadly defined as "the combination of methodologies in the study of the same phenomena" (Denzin, 1978: p291). Multiple methods can refer to the use of different methods to examine the same dimension of a research problem, or it can refer to multiple techniques within a given method to collect and interpret data. The strengths of the multiple methods are that a more complete holistic and contextual portrayal of the units under study is possible. As noted by Jick (1979), triangulation in a primarily qualitative study can potentially generate 'holistic work' or 'thick description', and quantitative techniques can highten qualitative research. The development of quantifiable schemes for coding complex data sets can also strengthen qualitative research.

Two important decisions must be addressed when planning mixed method research designs. Firstly, the extent to which the study will operate within one dominant paradigm and, secondly, whether to conduct the phases concurrently or sequentially (Johnson and Onwuegbuzie, 2004). While this study will employ mixed research methods, qualitative will be the primary paradigm. This is because the thesis primarily seeks to explore the ETO supply chain with rich, detailed data in a natural setting. The quantitative element adds to comparability. Phases will be conducted concurrently.

3.4 CASE RESEARCH METHODS

This section will review the specific package of research methods used in the thesis along with the strengths and weaknesses of different methods. The data collection methods are addressed first, followed by the data analysis techniques used. The following section gives a detailed description of how they are applied to different units of analysis.

3.4.1 Industrial Secondment

Research that is immersed in the field, such as ethnographic and action research, has been successfully used for producing 'thick descriptions' (Geertz, 1973). In this thesis, the immersion in the field takes the form of a 10 week industrial secondment to a case company. This secondment provides a structure for the case research. The researcher was 'embedded' in the workplace and was given a desk in the participating organisation. Lewis (2009) noted that prolonged engagement in the field can allow a researcher to better predict and interpret the meaning of events. Such immersion can also help researchers increase their access to otherwise unavailable data in organisations. It permits trust relations to develop, allows the researcher to collect data that are different in kind and quality from data produced by any other method (Michael and Urs, 1999). Evered and Louis (1981) noted the differences in data and data quality that is obtained from research 'inside' as opposed to 'outside' organizations. Some phenomena can only be uncovered, and an integrated understanding can only be achieved, by doing research actually in organizations (Michael and Urs, 1999). This approach provides improved access to data, and an intuitive understanding of the organization, all of which extends the external and internal validity of those data. The industrial secondment is an important part of the research process. It presents the opportunity to be immersed in the natural setting of an ETO supply chain, and provides a foundation for approaching different companies and elements within the system.

3.4.2 Observation and Process Mapping

As noted by Bryman and Bell (2003), many definitions of ethnography and participant observation are very difficult to distinguish. Both allude to the researcher immersing him or herself in a particular group for an extended period of time, observing behaviour, listening to conversations between others and conversations including the field worker. It often includes more than simply observation, and is often done in combination with interviews and collection of documents (Bryman and Bell, 2003). In the context of case research, Yin

(2003) argues that the strengths of observation are; that events are covered in real time, that context is captured and that insight can be provided into interpersonal behaviour and motives. The weaknesses are that observation can be time consuming and potentially costly, as well as selective. The event may also proceed differently because it is being observed (Yin, 2003).

Observation also relates to site and factory visits. Barker et al. (2000) referred to the importance of 'walking' the process and using mapping techniques to capture material and information flows. Process mapping is a popular starting point for the analysis of operations (Hines and Rich, 1997; Watson, 1994). 'Walking' the process involves observing selected sites or manufacturing processes, often accompanied by an employee to 'talk through' the process. A process can be defined as any activity which takes a set of input resources, which are then used to transform something or are transformed into outputs. Various process mapping techniques exist, which usually involve the construction of a model that shows relationships between activities, people, data and objects involved in the production of an output. The strengths of process mapping are that they provide an established method for documenting and analysing existing processes as well as improving or redesigning business processes (Biazzo, 2002; William et al., 1997). Hines and Rich (1997) proposed 7 different mapping tools. More recently process mapping has started to become more popular in the construction sector (Winch and Carr, 2001).

3.4.3 Interviews

Semi-structured interviews will be primarily used in this study. This form of interview involves designing a framework which encourages respondents to discuss their opinions and experiences. The semi-structured approach is suitable for research that is exploratory in nature. It allows respondents some freedom and flexibility to elaborate on topics of particular interest or relevance to their knowledge. As part of this method, a broad interview topic guide would be used to guide the interview. The interviewer would usually use a standardised interview schedule with set questions which will be asked of all respondents. A similar order and format is employed to enable comparison between answers.

The semi structured approach does offer scope for pursuing and probing for novel, relevant information, through additional questions often noted as prompts on the schedule and the interviewer frequently has to formulate impromptu questions in order to follow up leads that emerge during the interview. A key characteristic of the semi structured interview is the flexibility. The interviewee will pursue topics of interest along higher level themes while the researcher prompts and responds accordingly depending on the responses of different interviewees. Interviewees will not be forced to select specific options but may be steered towards the higher level themes outlined in the questions (Bryman and Bell, 2003; Saunders et al., 2007). Semi-structured interviews were chosen over the structured interview as the latter are more are suitable for collecting data that is largely factual, quantitative or non emotive and from businesses that have several features in common. They are particularly appropriate when the aim is to quantify the relative importance of different responses to questions about a set of well defined topics (Wass and Wells, 1994).

3.4.4 Archival Data

Barker et al. (2000) in the terrain scanning methodology for construction supply chains suggested that obtaining relevant archival and analytical information is an important part of the triangulation process, and can include previous analysis undertaken by companies, company literature and other documentation. Other sources of documentation include computer files, organisational maps and charts and previously collected data about a site. Yin (2003) suggested that the strengths of documentation are: that the sources are often stable and can be reviewed repeatedly, they are unobtrusive as they are not created as a result of the case study, and they are exact in terms of details. The weaknesses are: that information can be biased, as they are often produced for a specific purpose and audience, there is the potential for selective bias if a collection of documents is incomplete, and finally access may be deliberately blocked. Yin (2003) also pointed out that documents and archival data can be of central importance in a research project or only of passing relevance. In this research, documents are used as supporting sources of information.

3.4.6 Brainstorming

The importance of brainstorming when triangulating multiple data collection methods in supply chain management research has been highlighted by Naim et al. (2002). It shares similarities with a group interview where members of a group are interviewed in a relatively unstructured way about joint experiences. An interviewer will, typically, prepare some open questions and will also take on the role of facilitator during the group interview (Bryman and Bell, 2003) . Brainstorming provides an ideal way for members of a supply chain or system collectively to make sense of phenomena, problems and potential solutions. It also provides an important opportunity to make sense of a fragmented complex system. The task oriented, interaction-centred group interview has also been identified as a robust methodology to explore professionals' experiences and for them to describe that experience (Calder, 1994).

3.4.7 Cross case analysis

Eisnehardt (1989) suggested structuring analysis by considering within case analysis and cross case analysis. Cross case analysis consists of examining, categorising, tabulating, testing and recombining both quantitative and qualitative evidence from different cases. Cross case analysis is particularly important for highlighting and identifying patterns. The following list of data analysis strategies will be used, which have been adapted and synthesised from Yin (2003), Eisnehardt (1989) and Stuart et al. (2002):

- Tabulation of data relating to different variables or concepts;
- Listing of differences and similarities between different cases;
- Summary diagrams, data displays and flowcharts;
- Current state process maps;
- Compare data relating to different units of analysis and/or embedded units of analysis;
- Quantification of embedded units of analysis;
- Comparison of case study reports;
- Pattern matching (relating case data to a priori assumptions);

- Explanation building.

3.4.8 Interview Coding

Coding entails reviewing transcripts and field notes and giving labels to separate, compile and organise data into its component parts (Bryman and Bell, 2003). Strauss and Corbin (1990) distinguish three types of coding practice:

- *Open coding*. The process of breaking down, examining, comparing, conceptualising and categorising data;
- *Axial coding*. Data are put back together in new ways after open coding to make connections between categories. Codes are linked to context, consequences, patterns of interaction and to causes;
- *Selective coding*. The procedure of selecting the core category, systematically relating it to other categories, validating those relationships and filling in categories that need further refinement and development. A core category is the central issue or focus around which all other categories are integrated.

A further issue in coding is that of analysing group interviews and brainstorming sessions. An important consideration here is the extent to which whole group analysis, where the data is analysed at a group level without delineating individual contributions, and participant based analysis, where the contributions of individual participants are analysed separately within the wider context of the whole discussion, are used (Bryman and Bell, 2003; Saunders et al., 2007). It is proposed that both data analysis types will be used for the analysis of brainstorming sessions. While coding is a recognised technique for analysing concepts and categorising data, a number of dangers are highlighted. There is the possibility of losing the context of the original data, the fragmentation of data and the contamination of words and behaviours.

3.4.9 Quantifying data and Descriptive statistics

According to Tashakkori and Teddlie (2003) transforming qualitative information into numerical codes that can be analysed statistically can provide a richer understanding of variables. This might include frequency counts of certain themes responses behaviours and events or a rating of strength or intensity of these behaviours or expressions (Tashakkori and Teddlie, 2003). Researchers can start with in depth process data and then systematically list and code qualitative incidents according to predetermined characteristics, gradually reducing the complex mass of information to a set of quantitative data that can be analysed using statistical methods. Assumed that the original data is complete and the coding reliable, the advantage of the quantification process lies in the systematisation of process analysis (Langley, 1999).

Van de Ven and Poole (1990) transformed incidents into a series of binary codes associated with categories forming a 0-1 matrix that the authors called a 'bit map'. This type of quantification allowed the researchers to search for pattern and compare data effectively across cases. This technique is also useful for comparing dynamic relationships between events and categories. However, Langley (1999) highlighted the danger of losing the richness of data that qualitative research can yield by relying solely on a quantification strategy. Once data has been transformed into quantitative data, descriptive statistics, such as bar charts, pie charts and histograms, might be used to summarise and organise frequency counts and binary codes (Tashakkori and Teddlie, 2003).

3.4.10 Cause and Effect

Cause and effect diagrams help to depict relationships between adverse events and their contributing factors. The tools are popular in the quality literature (Aguayo, 1991) , where the 'five whys' analysis has been proposed as a tool for exploring root causes of problems. In this technique, a tree diagram is developed by asking 'why' (the cause) five times before a root cause is established. Cause and effect analysis can also take the form of Ishikawa diagram. This uses brainstorming to highlight possible contributing causes of a particular problem. The same technique is often referred to as a 'fishbone' diagram due to the form of the diagram (Bicheno, 2006). Cause and effect analysis is also an important part of systems dynamics modelling, where the underlying objective is to determine cause-and-effect relationships and thereby to understand the forces that have led to a particular system state

(Sterman, 1989). Causal influence diagrams, in particular, have been extensively used in systems dynamics.

Cause and effect analysis techniques are important as they illustrate the causes of problems in concise and visual ways, and often bring stakeholders together to find the source of a problem. One of the key analytical tools for auditing a supply chain, as demonstrated in the quick scan approach, is a cause and effect analysis (Naim et al., 2002). The 'terrain scanning methodology', a supply chain diagnostic tool for the construction industry, also emphasizes the importance of cause and effect analysis for construction supply chains (Barker et al., 2000). They have been used effectively by Barker et al. (2004) to investigate time compression potential in the design process and also as a way of examining supply chain uncertainty (van der Vorst and Beulens, 2002).

3.5 SUMMARY

In this chapter, three main research paradigms have been described including positivism, critical realism and social constructivism. The author's stance has been highlighted as a critical realism. The use of multiple case study research was justified, taking into account the research aim and questions. Advantages and disadvantages of case study research have been discussed. A mixed methods research design was also specified, with qualitative methods playing the dominant role and quantitative techniques playing a supporting role. Qualitative and quantitative techniques will be used concurrently.

This chapter has also described and defended the multiple data collection techniques that will be employed in the study. First of all, the strengths and weaknesses of the different approaches are addressed. These techniques include interviews, process mapping, observation and site visits, brainstorming and archival data. This chapter has also described the data analysis techniques used in the study. Multiple data analysis techniques are used including cross case analysis, process maps, interview coding, quantification, description statistics, cluster analysis, brainstorming and cause and effect analysis.

SUMMARY OF CHAPTER 3 AIMS

1.Review research philosophy literature and explicate the philosophical position adopted

- The positivist, critical realist and constructivist research philosophies have been reviewed. A critical realist research stance is adopted, and key implications for the thesis have been articulated.

2.Critically review research methods that will be used in the study

- The strengths and weaknesses for each data collection and data analysis technique have been discussed along with the strengths and weaknesses associated with case research.

3.Justify multiple case study research and mixed methods design

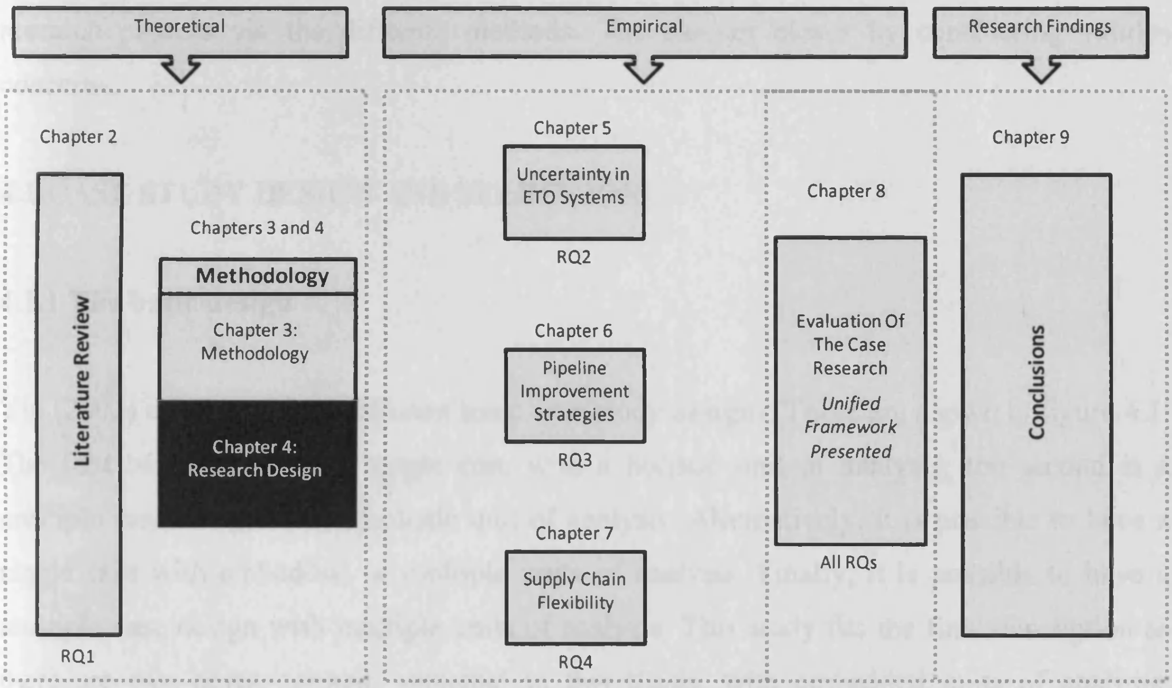
- A multiple case research strategy using a mixed method design has been justified

CHAPTER 4

RESEARCH DESIGN

CHAPTER 4 AIMS

1. **Introduce the basic case study design and case selection criteria**
2. **Link research questions with research methods**
3. **Identify the units of analysis**
4. **Describe the application of research methods to the units of analysis**
5. **Explain the tactics used to address validity concerns**



4. INTRODUCTION

This chapter develops the research design. An overview of the case study design is presented. This is followed by a description of the units of analysis identified in the study. This also includes the case selection criteria and logic. A description of how the data collection and analysis techniques identified in the previous chapter are applied to different units of analysis and the research questions is then offered. A final data collection phase, the evaluation interviews, is then described. The detail of the overall research approach is then summarised, giving an overview of all the field work conducted over the course of the research process via the different methods. The chapter closes by considering validity concerns.

4.1 CASE STUDY DESIGN AND SELECTION

4.1.1 The basic design

Yin (2003) envisaged four different basic case study designs. These are shown in figure 4.1. The first basic design is a single case with a holistic unit of analysis; the second is a multiple case design with a holistic unit of analysis. Alternatively, it is possible to have a single case with embedded or multiple units of analysis. Finally, it is possible to have a multiple case design with multiple units of analysis. This study fits the final description as there are two cases, termed 'systems' in this thesis, with embedded units of analysis. Embedded case studies occur when, within a single case, attention is given to a subunit or subunits. An embedded design can serve as an important device for focussing a case study enquiry (Yin, 2003). The position of this research is also shown in Figure 4.1.

As noted by Stuart et al. (2002), in operations management the central focus is on the organisation's operational systems, each built up from their subsystems. Each component subsystem adds complexity, making it more difficult to see and substantiate findings. A starting point is to break the range of organisations down into manageable, comparable groups. The business systems engineering approach provides a useful approach for thinking about this complexity and identifying manageable and comparable groups, termed subsystems. A system may be described as recognizable whole which consists of a number of parts that are connected up in an organised way. This recognizable whole includes a boundary, an environment, a purpose and emergent properties (Waring, 1996). According to Watson (1994) business system engineering is "an approach to designing business processes in a structured way that maximises both customer value and enterprise performance" (Watson, 1994: p42). A systems philosophy demands that an uncoordinated approach is replaced by a framework in which the identities of the separate parts are subsumed by the identity of the total system. Via the system engineering approach, the individual elements and subsystems are designed and fitted together to achieve an overall system purpose, where the right parts must be connected and in balance if the system is to produce the desired results (Parnaby, 1995; Towill, 1997b).

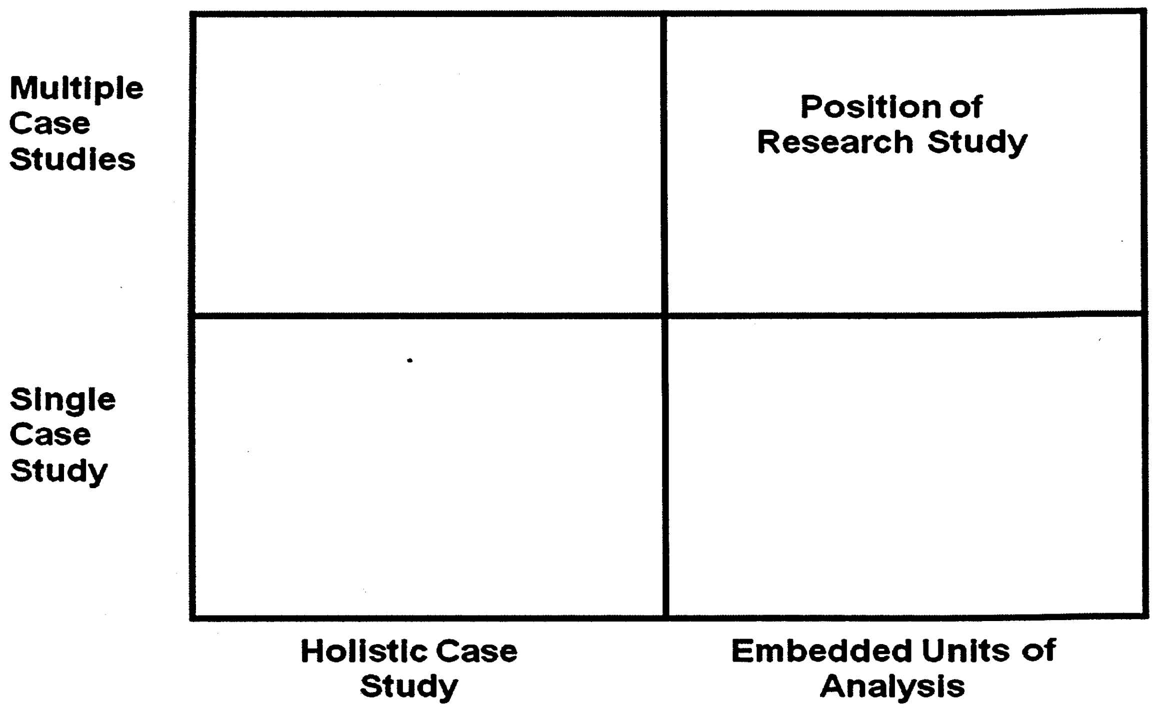


Figure 4.1: Positioning of case research design (Source: adapted from Yin, 2003)

A system thinking perspective provides a foundation for conceptualization of the objects of study in this thesis as well as a framework for guiding the study of a system. Consideration of system boundaries and elements contributes significantly to the 'carving up' and definition of the objects of study. At the system level, the focus of this thesis is the ETO system. A robust definition of this developed throughout the thesis. Within the ETO system a distinction is made between a 'network co-ordinator', a 'project' and a 'supplier pipeline'. These are the embedded units of analysis in the thesis. The following provides an overview of these units of analysis:

- *Network Co-ordinators.* This is the focal organization of the study and assumes responsibility for configuring the network of suppliers, subcontractors and interdependent organizations that work together to deliver projects. The network co-ordinator has been described elsewhere as more like a broker than a producer, which specializes in co-ordinating an extensive network of buyers and suppliers (Cravens and Piercy, 1994).
- *Projects.* A project can be defined as "a set of activities with a defined start point and a defined end state which pursue a defined goal using a defined set of resources" (Slack et al., 2004) or "non-repetitive activity that is goal orientated, has a particular set of constraints and a measurable output" (Maylor, 1999). In the context of this study, projects refer to the specific projects that the network co-ordinator organisation is currently involved with.
- *Supplier pipelines.* Berry et al. (1998) defined the pipeline as the delay between generating an order and the receipt of that order into stock. Aitken (2003) defined it as the specific operational mechanisms and procedures that are employed to service a specific product. In this study it relates to all those activities between generating an order and the integration of the order with the site.

Two systems are investigated in this thesis. Figure 4.2 depicts these two systems. The boundaries and units of analysis can be clearly seen. The projects are labelled P1, P2, P3, P4 and P5, and the pipelines are labelled cases A through to L. System 1 comprises 1 network co-ordinator, 3 projects and 9 pipelines. System 2 comprises 1 network co-ordinator, 2 projects and 3 pipelines. The figure also shows the interrelationships between pipelines and projects. The supplier pipelines for each project are indicated by the arrows. For each of the three projects the network co-ordinator has to liaise with clients, design consultants, such as architects and structural engineers, and regulatory bodies, such as local councils, in order to complete the project.

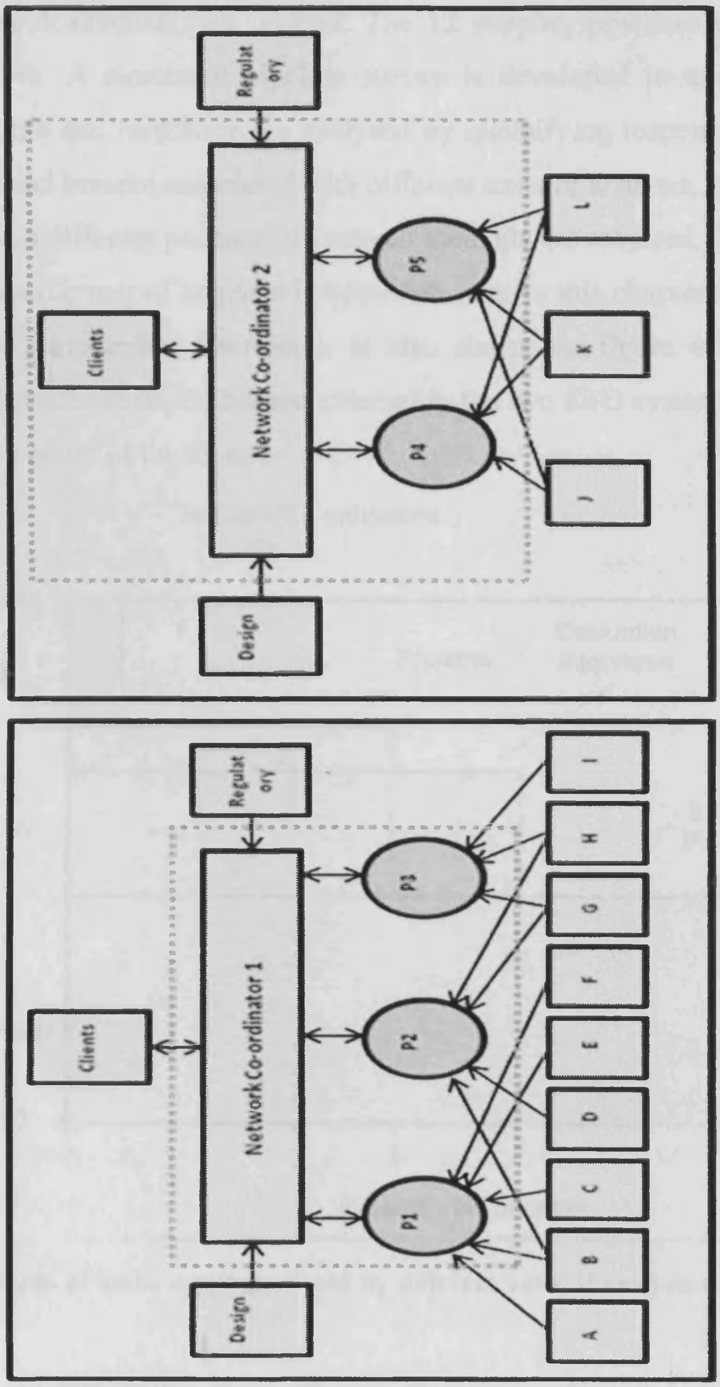


Figure 4.2: The two ETO systems and the units of analysis

The design of this study aims to balance breadth and depth of knowledge. Figure 4.3 shows that the research design offers both scope and depth of understanding. The two network co-ordinators are investigated in depth with less structured and more qualitative methods. The five projects offer increasing breadth with slightly less depth. More structured methods, including mixed research methods, are utilised. The 12 supplier pipelines offer the most breadth and least depth. A structured pipeline survey is developed to analyse different components of lead time and responses are analysed by quantifying responses. Due to the varied levels of depth and breadth associated with different units of analysis, and the number of cases for each level, a different package of research methods are required. The package of research questions for each unit of analysis is described later in this chapter. The final data collection phase, the 7 evaluation interviews, is also shown on figure 4.3. These have moderate breadth and moderate depth, but are external to the two ETO systems that make up the case study research phase of the thesis.

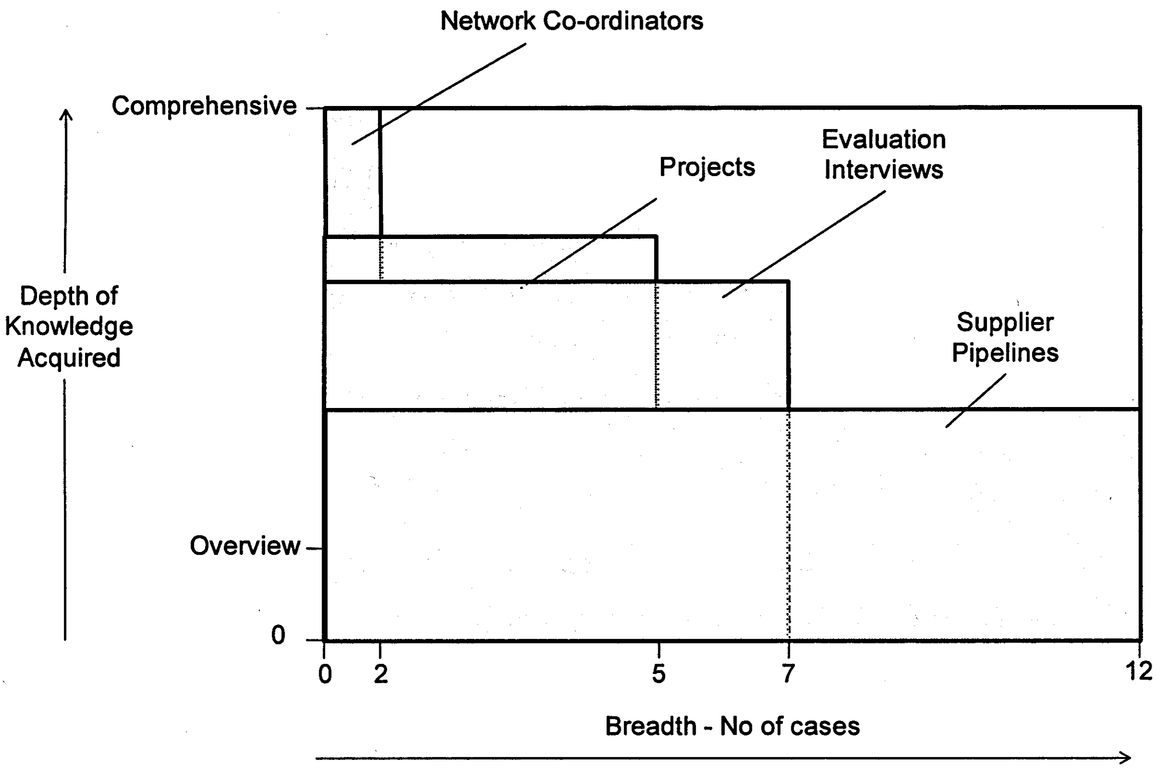


Figure 4.3: Scope and depth of understanding offered by different units of analysis (Source: adapted from Towill et al. 2001)

4.1.2 Case Selection

According to Stake (1994), while case study research is not sampling research, some cases may do a better job than others, so when selecting cases it is important to maximise what one can learn about the phenomena under study. Cases are often chosen for theoretical, not statistical, reasons. Cases may be chosen to replicate previous cases or extend emergent theory, or they may be chosen to fill theoretical categories and provide examples of polar types (Eisenhardt, 1989). This study employs a deliberate theoretical sampling plan for different units of analysis.

The network co-ordinator was selected based on a number of criteria. The most important characteristic of the network co-ordinator in selecting the focal company was the likeness of the supply chain with the expected characteristics of an ETO supply chain as specified in the literature review. They were also chosen based on the willingness of the organisation to engage with academic research. In particular, they were chosen on the basis of motivation to address the uncertainties that exist within their supply chains and explore supply chain strategies to enable them to cope with such uncertainty. Companies demonstrating and engaging in innovative supply chain initiatives were sought out. Both network co-ordinators were partners on an EPSRC funded research project at Cardiff entitled McCLOSM (Mass customised Logistics for Sustainable Manufacturing). McCLOSM was a 5 year industry linked project examining frameworks for logistics and supply chain across the 3 sectors of steel, construction and retail, running between 2004 and 2009. This thesis draws on the construction related activities undertaken in the project, which the author was solely responsible for.

The network coordinator in System 1 is a main contractor based in the South of the UK and has a turnover of £70 million with a workforce of around 550 employees. Major clients include housing associations, care scheme operators, commercial and industrial concerns and schools. The organisation specialises in delivering projects on a design and build basis, which has been described elsewhere as an integration coalition, where a client transfers the majority of risk to a main contractor who then takes responsibility for the design and execution of the project (Winch, 2002). The network coordinator has a total network of over 750 suppliers, which it configures based on the needs of each project. It has won numerous awards for best developments, and has been included in a number of best practice guides written about client partnering and supply chain management.

The network co-ordinator in System 2 is a global construction management company with a turnover of £530 million and 2800 employees. The organisation specialises in large commercial tower buildings delivered on a construction management contract basis. This contract type has been described as a mediated coalition which is characterized by the appointment of a construction manager who is responsible for managing trade contractors (Winch, 2002). The value and duration of the projects is much greater than in System 1. The company was voted in the top 5 of the Sunday Times 'top track' in 2008 and was also awarded the construction management organization of the year prize by a leading trade magazine. The organisations approach to supply chain management and collaboration are well recognized in the industry.

Once the network co-ordinators were selected the next step was to identify suitable projects and supplier pipelines to study. Projects and supplier pipelines were both selected via 'snowball sampling' (Sanderson and Cox, 2008; Scarbrough et al., 2004). This process includes using recommendations regarding areas of focus, and interviewees suggested by key industrial contacts from the focal organisations, which in this case was the network co-ordinator. Yin (2003) suggested defining a set of operational criteria whereby candidates will be deemed qualified to serve as cases. An illustration of the snowball sampling process and the operational criteria for the different units of analysis is shown in figure 4.4.

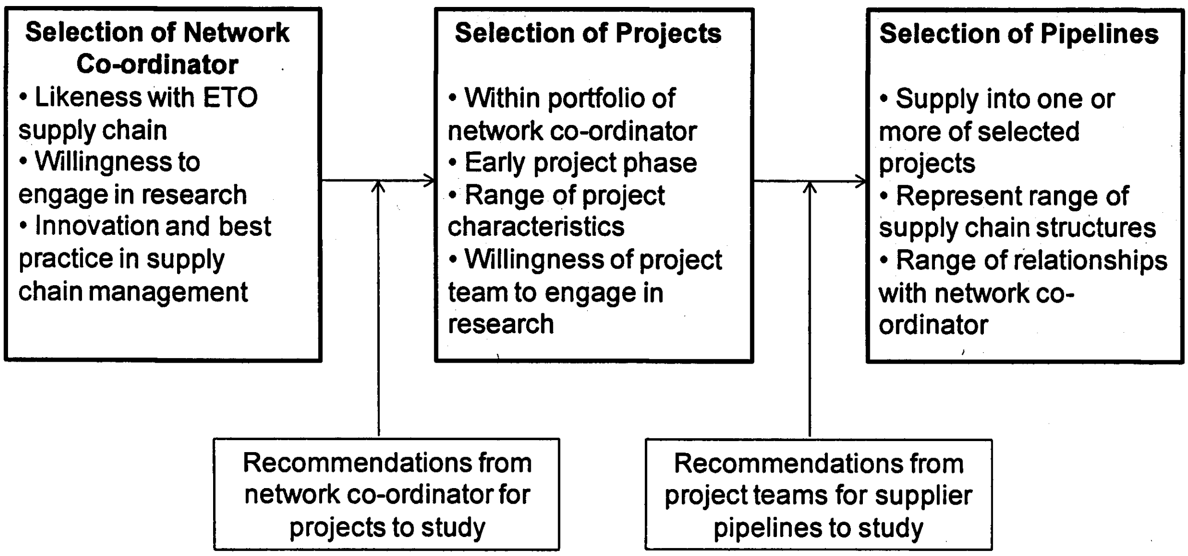


Figure 4.4: The snowball sampling process and operational criteria for different units of analysis

A set of criteria to screen different candidate projects was developed. Firstly, the phase that the project was in at the time of selection was used as a selection criterion. Projects were favoured if they were at the beginning of the construction phase. This would allow the researcher to visit as the site develops and offer the opportunity to observe construction processes as they took place. Secondly, pragmatic concerns such as the willingness of the project management team to engage with the researcher were also considered. Finally, build characteristics such as value, time constraints, construction method, and logistical challenges were also considered for project selection. The intention was to include projects with a range of values, construction methods and logistical challenges. A more detailed description and analysis of these projects is offered in chapter 5. Table 4.1 shows a summary of the projects selected. Eight projects from network co-ordinator 1 were short listed. Three of these were chosen which are shown in the table as projects 1, 2 and 3. Only two projects from network co-ordinator 2 fit the criteria, and are shown in the table as projects 4 and 5.

	Project 1	**Project 2**	**Project 3**	**Project 4**	**Project 5**
Value	£4.7m	£3.2m	£66m	£155m	£100m
Time Period	74 Weeks	68 Weeks	60 Months	3 Years	2 Years
Customer Type	Social Housing Developer	Social Housing Developer	Consortium of private and government	Commercial Developer	Commercial Developer
Project Type	Social and Private Housing	Social Housing	Regeneration Project	Large Commercial Tower	High Specification Office Building
Construction Method	Concrete Frame	Timber Frame	Timber Frame	Concrete Frame	Concrete frame
Building Details	32 Flats	37 Flats	442 new homes, 325 refurbished. 3 commercial buildings	21 Storey 3 Tier Glass facade Tower (586,000sqft)	6 Storey Office Block (100,000sqft)
Contract Type	Design and Build	Design and Build	Private Finance Initiative	Construction Management	Construction Management
Network Co-ordinator	1	1	1	2	2

Table 4.1: Summary of projects in the study

Supplier pipelines were also recruited via snowball sampling, but a specific selection criteria was also developed. In order to analyse different pipelines in ETO supply chains, the researcher was given access to contact details for suppliers and subcontractors with recommendations as to which may be suitable for research. Suppliers were then approached according to three criteria. Firstly, only suppliers that were involved with the projects selected were considered. Secondly, the range of suppliers were chosen to represent the spread of supply chains structures from buy-to-order, where components are only purchased when a customer order exists, to MTS, where finished goods are held in a fixed location awaiting customer orders (Hoekstra and Romme, 1992; Naylor et al., 1999). Thirdly, suppliers were chosen to represent a range of categories of supplier relationships with the network co-ordinator. Table 4.2 shows the details for the different supply pipelines that participated in the pipeline survey, and their relationships to projects and network co-ordinators. These relationship categories are described in more depth in chapters 7 and include strategic partners, preferred suppliers and approved suppliers

Case	Sector	Employees	Turnover	Network Co-orindator	Projects	Primary Supply Chain Structure	Relationship with Network Co-ordinator
A	Elevators and Escalators	44000	£3.83bn	1	1	ATO	Strategic Partner
B	Windows	20-30	£4.5m	1	1 and 2	MTO	Preferred
C	Pre-cast Concrete	350	£230m	1	1	MTO	Preferred
D	Roof Trusses	150	£8m	1	2	MTO	Preferred
E	Metalwork	10,20	£1.25m	1	1	BTO	Approved
F	Brickwork	234	£15.7m	1	1	MTS	Approved
G	Timber Frame Systems	1400	£420m	1	2 and 3	MTO	Strategic Partner
H	Doors	205	£22.5m	1	3	BTO	Preferred
I	Builders Merchant	10600	£2bn	1	3	MTS	Approved
J	Paint	67	£11.5m	2	4 and 5	MTS	Strategic Partner
K	Modular Bathrooms	425	£53.8m	2	4 and 5	ATO	Strategic Partner
L	Drylining/Safety systems	52-100	£14m	2	4 and 5	BTO	Strategic Partner

Table 4.2: Summary of the supplier pipelines

4.3 APPLICATION OF THE RESEARCH METHODS

The next step in conducting the case research was the development of research instrumentation and an accompanying research protocol. This section will describe the specific package of research methods used in the thesis. The instruments refer to the particular methods to be employed, and the protocol contains the procedures and general rules that should be used, as well as who or from where the different kinds of information are to be sought when using the instruments (Voss et al., 2002). The case study protocol contains the instruments as well as the general rules to be followed in using the protocol. It guides the investigator in carrying out the data collection and is essential when doing a multiple case study to ensure reliability across different cases (Yin, 2003). It has been noted that triangulation of different data collection methods can help the development of converging lines of inquiry (Eisenhardt, 1989; Yin, 2003). Table 4.3 provides an overview of the data collection methods used in the study for different units of analysis.

Method	Network Co-ordinator	Project	Supplier Pipelines
Aim	Explore Supply Chain Flexibility	Identify Project Uncertainties	Explore Supplier Pipelines
Protocol	Appendix 1	Appendix 3	Appendix 4
Interviews	Major process teams	Site Management	Recommended Contact
Process Mapping	Supply chain process mapping. Mapping of requisition and buying process.	Site processes	Input – Output process maps. Individual process maps for pipelines. Generic process maps for all pipelines.
Observation	Team meetings, management processes and systems	Site visits, visual control boards	Factory visits, visual control boards, systems demonstrations.
Brainstorming	Regular meetings with key stakeholders to brainstorm findings so far and verify data. Also used to 'map' supply chain flexibility onto uncertainties	Brainstorming sessions to develop generic uncertainties, highlight cause and effect of uncertainties and to establish impact/ likelihooh	Brainstorming sessions to establish relationships in causal modelling diagrams.
Archival Data	Process and procedure documents, organisational charts, web site information, records of supplier performance, lead time data, company reports.	Project specific documents. Drawings, project plans, requisition forms, bills of materials, order schedules.	Web sites, company reports, Process and procedure documents, lead time data.

Table 4.3: Overview of data collection techniques

Table 4.4 provides an overview of the data collection methods used in the study for different units of analysis.

Method	Network Co-ordinator	Project	Supplier Pipelines
Cross case analysis	Compare purchasing behaviour in two different ETO systems.	Compare embedded units of analysis. Find commonalities of uncertainties across 5 Projects.	Compare embedded units of analysis. Compare 12 Pipelines.
Process Maps	Supply chain process mapping. Mapping of requisition process and purchasing models.	Site processes	Input – Output process maps. Individual process maps for pipelines. Generic process maps for all pipelines.
Interview coding	Interviews with process teams coded	1) Code individual project profiles to create a generic uncertainty profile 2) Categorise uncertainties under sources of supply chain uncertainty	1) Code 'problems in the pipeline' 2) Code 'sources of competitive advantage'
Quantification	Not used	Binary coding mapping techniques for flexibility types and uncertainties	Binary coding for analysis of pipeline interviews.
Descriptive Statistics	Not used	Graphs and charts for uncertainties identified	Graphs and charts for lead time data
Cluster Analysis	Not used	Investigate clusters identified in binary coding	Investigate clusters identified in binary coding
Brainstorming	Regular meetings with key stakeholders to brainstorm findings so far and verify data. Also used to 'map' supply chain flexibility onto uncertainties	Brainstorming sessions to develop generic uncertainties, highlight cause and effect of uncertainties and to establish impact and likelihood of uncertainties	Brainstorming sessions to establish relationships in causal modelling diagrams.
Cause and Effect	Cause and effect analysis of uncertainties	Cause and effect analysis of uncertainties	Causal modelling for pipeline problems and solutions

Table 4.4: Summary of data analysis techniques

The remainder of this section offers a detailed description of the data collection techniques and data analysis techniques that were used for the 3 units of analysis.

4.3.1 The Network Coordinators

As previously noted, the network coordinator represents the focal organization for the system. For system 1 the researcher undertook a 10 week industrial secondment. The researcher was given a desk at the case company and was placed under the care of the 'business improvement manager' and was seated with the 'business improvement team'.

Prior to the secondment a case study protocol was developed. This consisted of research objectives, provisional questions, planned activities, planned activities, data collection and analysis techniques, major deliverables and resources required. An industrial workshop was organised to pilot the protocol and was presented to members of the McCLOSM project, including practitioners from retail, steel and construction sectors, as well as academics from the McCLOSM team. Along with comments from the business improvement manager at the network coordinator, minor revisions were then made to the case protocol. The protocol then led to the development of a case study brief, which is shown in appendix 1.

The secondment afforded the opportunity to sit in team meetings, encounter informal chats in corridors and get insights into the minutiae of how operations are conducted and managed. Semi-structured interviews were carried out with major process teams, including 'preconstruction', 'construction', 'technical' and 'new business' teams, and the researcher was granted permissions to sit in different team meetings. Organisational charts and structures were used to select relevant interviewees. Supply chain managers, buyers, quantity surveyors, technical design staff, logistics and business improvement employees were all interviewed as part of the protocol. An interview log is shown in appendix 2.

The researcher was given access to a range of archival data types. This included access to internal systems and databases, publicity material, in house magazines, process maps, protocols and procedures. It also included access to marketing literature such as presentations, public relations material and case study leaflets. Records of supplier performance and key performance indicators held on a database were also used. Brainstorming was also used to help synthesize different data types. Regular meetings with the business improvement manager were held to brainstorm findings so far and verify data. This also helped to indentify new avenues for data collection and refine ideas. Minutes of brainstorming sessions were documented by the researcher. Process maps and models were developed and then presented at brainstorming sessions.

Due to resource constraints, a secondment was not conducted for the network coordinator in system 2, but the researcher was given free access to visit and collect data, and the same protocol and case study brief were used. A research diary and folder was maintained for each system.

4.3.2 Projects

The focus of the project unit of analysis was the identification of project uncertainties and risks. Five sites across the two systems were visited. Some were visited more than once to observe site progress. Visits to the sites are also shown in the fieldwork log shown in appendix 2. In all of the site visits the researcher was accompanied by members of site management and other staff from headquarters. This gave the researcher the opportunity to ask questions, clarify and observe processes during the tour of the site. Photos, process maps and notes were recorded during these visits.

Semi structured interviews were conducted with site managers and project managers. A template was designed for interviewing and capturing data from project managers based on risks and uncertainties across all the stages of a project. This is shown in appendix 3. Risks and uncertainties were probed against the project stages identified in the project protocol suggested by (Winch and Carr, 2001). The stages they suggest are define need, establish viability, conception, scheme design, detailed design, production planning, main trades, finishing trades, commissioning and facility management. Documents, such as project plans, project designs, requisition forms, bills of materials, tender documents, photos and site logs were provide to support other forms of data collection.

For the analysis of project uncertainties, a risk and uncertainty register, in the form of a spreadsheet, was developed for each project based on the data collected from semi structured interviews with site management teams. The uncertainties for individual projects were then categorized to develop a more generic list of uncertainties. A final spreadsheet was developed listing the generic uncertainties, grouping them by sources of supply chain uncertainty described in Mason-Jones and Towill (1998).

Once a generic list of uncertainties was developed, the next step in the research protocol was to establish the likelihood of different uncertainties developing into a negative outcome and the potential impact in terms of cost and time penalties. These two dimensions, which are well documented in the risk management literature (The Institution of Civil Engineers, 1998), are used here to indicate the relative importance of the different uncertainties. A brainstorming activity was conducted and uncertainties identified were plotted on a graph with the axes 'impact' and 'likelihood'. This activity was supported by a clustering and brainstorming exercise, including business improvement manager from network co-ordinator 1 and a business unit director from network co-ordinator 2, with the aim of producing a cause and effect diagram. The results of the cause and effect analysis are mapped onto the dimensions of the supply chain uncertainty circle to provide an insight into the causes and relationships between uncertainties in the ETO system.

In chapter 6 a binary coding mapping exercise is undertaken to identify whether uncertainties can be mitigated by vendor and sourcing flexibility, the two antecedents of supply chain flexibility. The uncertainties identified in the study were listed in a table column. Vendor and sourcing flexibility were then listed across the top of the table in order to 'map' them against uncertainties. The table was then populated with binary coding to indicate which antecedent can be used to mitigate the different uncertainties. A '0' indicates that it cannot mitigate the uncertainty, and a '1' indicates that it can be used to respond to a specific uncertainty. The decision about whether or not a flexibility type is required to mitigate an uncertainty was reached by a triangulation of sources of information:

- *Literature and interviews.* The researcher used the literature to establish appropriate applications of flexibility types and coded interviews from site management teams which included suggestions as to the ways in which uncertainty can be mitigated were used.
- *Brainstorming sessions.* Once a preliminary matrix was developed the results were brainstormed with the business development manager from network co-ordinator 1 and a business unit director from network co-ordinator 2.
- *Evaluation presentations.* The results were then presented to a range of organisations to evaluate the results.

4.3.3 Supplier Pipelines

A 'pipeline survey' was designed to gather exploratory data about a supplier or subcontractor, which utilizes a mix of open and closed questions under different headings adapted from an approach used by Berry et al. (1998). The interview prompt list was arranged under different headings relating to company details, products and services, external environment (suppliers and customers), internal environment (focused on internal production issues) and strategic capabilities relating to flexibility. A further section investigated lead times, based on a template designed to probe areas of variability and uncertainty for the pipeline, and explores problems and sources of competitive advantage in the pipeline.

The lead time analysis section probed areas of variability and uncertainty across 5 generic components of the order-to-delivery pipeline: design, procurement, manufacture, transport and site integration. Three point-time estimates for these generic pipeline activities were established, along with the key problems experienced in the pipeline. Companies were asked to give a "most likely", an "optimistic" and a "pessimistic" lead time for the different activities in the pipeline. In most cases, sales and manufacturing personnel were able to quote figures. In others, they were able to check records for values. Companies also were asked to quote a three-point estimate for the overall cycle time that they quote to customers. Lead time information that was collected from each supplier was inserted into a spreadsheet for analysis. The pipeline survey protocol is shown in appendix 4. In some cases, these interviews were accompanied by factory visits and tours through the business functions. A log of pipeline survey field activities is shown in appendix 5.

Lead time estimates were inserted into a spreadsheet to enable exploration by descriptive statistics. Bar charts and scatterplots were used to investigate various aspects of the lead time. The pipeline survey was analysed by coding responses by interviewees. Two areas are focused on the problems that are experienced in the pipeline and the sources of competitive advantage in the pipeline. A binary coding technique was used to code responses into theoretically meaningful categories. These themed responses were then consolidated on a spreadsheet. Input – output process maps were developed to show the raw materials and resource inputs for each supplier and the resulting outputs. An example of a simple process map for the focal company in pipeline K is shown in appendix 6. It shows key inputs and outputs at various process stages with key enablers for different processes shown in vertical text. After the process maps were completed, and the interviews written up, they were emailed to interviewees for verification.

4.3.4 Evaluation Interviews

As noted by Easterby-Smith et al. (2008), an underlying concern for researchers of all persuasions is that a piece of research stands up to outside scrutiny. This section describes how the case research in this thesis was evaluated using outside scrutiny. According to Lincoln and Guba (1985), 'member checking', whereby data, analytic categories, interpretations and conclusions are tested with members of stakeholder groups, is a crucial technique for establishing the credibility of research. This could come in the form of reporting findings to those from whom the data was originally tested or knowledgeable individuals from relevant groups. The researcher must then hear and weigh their meaningfulness and, unless the researcher has reason to doubt the integrity of informants, a member check is valid way to establish the meaningfulness of findings and interpretations and provides a strong foundation for convincing readers and critics of the authenticity of research.

Evaluation presentations were made to key stakeholder groups. The evaluation interviews are important as they provide a method for exposing the findings of the case research outside of the two case systems. The interviews offer findings that help to establish the potential to generalise the findings to different ETO construction environments. The aims of this activity were as follows:

1. Assess the accuracy, completeness, value, fairness and perceived validity of the findings by external review;
2. Evaluate the extent to which the findings can be generalised to different ETO construction sectors;
3. Evaluate the strengths, weaknesses, opportunities and threats associated with the research;

4. Enhance and enrich findings with evaluative empirical data;
5. Identify avenues for further research.

Potential participants were approached with standard email stating the above aims and giving a brief overview of the research findings. If this invitation was accepted a presentation was made to the participant. At the beginning of the presentation participants were reminded of the aims and the opportunity to ask questions and make comments was offered at any time during the presentation. If no comments were forthcoming the researcher prompted a response by probing for thoughts on key slides. A paper copy of the presentation was given to participants to read after the activity to allow more detailed scrutiny after the presentation had been made. At the end of the presentation, the interviewee was asked to identify the strengths, weaknesses, opportunities and threats associated with the research. The interviewees were also asked about the extent to which findings could be applied to their respective ETO construction sectors.

Table 4.5 provides a summary of the evaluation interviews. This selection process was purposeful, and had the objective of gathering feedback from a range of sectors and a wide range of supply chain members. A purposeful selection criterion was developed based on the units of analysis identified in the case research. As the construction sector provides the arena for the case research, the interviewees were targeted to cover a range of sub-sectors from the construction industry. Potential interviewees were also approached with the intention of covering a range of organisational types including clients, manufacturers, network co-ordinators, design, logistics and organisational bodies.

Table 4.5 shows that the interviewees were from a range of ETO construction sectors, house building, commercial buildings, civil engineering and government bodies, as well as representing a range of organisation types including clients, manufacturers, network co-ordinators, design, logistics and organisational bodies. It is also important to note that all interviewees were experienced, respected professionals in senior roles in their respective sectors.

Organisation Type	**Sector**			
	House-Building	Commercial Buildings	Civil Engineering	Government
Client			Interviews 5 & 6	
Manufacturer				
Network Co-ordinator			Interview 4	
Architect/Design engineer	Interview 1			
Logistics	Interview 2			
Organisational Body	Interview 3			

Table 4.5: Overview of evaluation interviews

4.3.5 Summary of empirical data collection

This section seeks to bring together all the different data collection phases of the study. Table 4.6 presents a summary of the contact with industry across the different data collection phases, showing the frequencies of different data collection activities. Interviews were the most numerous data collection technique with a total of 38. This was followed by site and factory visits which amounted to 14 across both systems.

Eight brainstorming sessions were conducted in total, one of which involved members from both systems. These are shown in the detailed log in appendix 2, and are also summarised in chapter 5, which makes extensive use of the brainstorming sessions (see table 5.1). Sessions 1 and 2 aimed to confirm the scope, scale and focus of the research. Sessions 3, 4 and 5 aimed to identify and consolidate supply chain uncertainties. The spreadsheets for different projects, as well as the generic uncertainty profile were discussed in these sessions. Sessions 5, 6 and 7 investigated the cause and effect of uncertainties. A 'post-it-note' exercise was undertaken, whereby uncertainties and their relationships were established by the group by writing, moving and agreeing on the position of post it notes showing the cause and effect of uncertainties. This is a popular technique used in lean process mapping (Hines et al., 1998; Hines and Taylor, 2000). Sessions 6, 7 and 8 sought to identify the likelihood and impact of uncertainties. Post it notes, with the generic supply chain uncertainties written on them, were added to a large board with the axis impact, running from high to low, and 'likelihood', showing high to low. These sessions aimed to bring consensus on the positioning of these uncertainties relating to likelihood and impact. These brainstorming sessions were used to create a cause and effect diagram for the supply chain uncertainties, along with an assessment of the impact and likelihood of the different uncertainties.

Type of data collection	**System 1**	**System 2**	**Both Systems**	**Evaluation Interviews**	**Total**
Industrial Secondment	1	0	0	0	1
Interviews	22	9	0	6	37
Brainstorming	5	2	1	0	8
Team Meetings	3	0	0	0	3
Site/Factory Visits	9	5	0	1	15
Supplier Training Days	0	1	0	0	1
Company Presentations	0	3	0	0	3
Total	40	20	1	8	67

Table 4.6: Summary of contact with industry

The supplier training day attended for system 2 was an executive meeting for all suppliers that fall into the 'strategic partner' category (chapter 7 develops and defines the term strategic partner). The researcher was invited to this event in order to better understand the way that the network co-ordinator interacts with suppliers, and in order to make contacts for possible investigation via the pipeline survey technique. This event included presentations from the chief executive of the network co-ordinator in system 2, as well as company presentations from suppliers and manufacturers. The event was intended to give suppliers an update of prospective work and projects that the company is bidding for, as well as to reinforce commitment to training and getting people to work together. The events give suppliers a chance to build links with each other and feed their input into training for strategic suppliers.

The table also shows that system 1 had much more data collection points, and represents a much more extensive case study that in system 2. There are a number of reasons for this. Firstly, system 1 was the first of the two systems studies to be studies and, therefore, there was an exploratory aspect to this part of the investigation. As noted previously in this chapter, there is often iteration between data collection, data analysis and research design in case study research. When the researcher started to investigate system 2 the aims and data collection requirements were much clearer. Secondly, the network co-ordinator had a specific interest in developing 'strategic partners', and did not wish for the researcher to focus on other categories of supplier as in the case of system 2. Finally, practical considerations had to be considered, including the amount of time and financial resources available to the researcher.

4.4 VALIDITY

The strengths and weaknesses of case research have been discussed earlier in this chapter. This section will address some of the concerns relating to rigour, generalisability and other validity issues. According to Yin (2003), four tests for judging the quality of research designs are common to all social science methods. These four tests include construct validity, internal validity, external validity and reliability. These concerns will be addressed in the research design through the tactics outlined in table 4.7, and will now be addressed in turn.

4.4.1 Construct validity

Construct validity refers to establishing the correct operational measures for the concepts being studied. An important concern for this research has been ensuring that models and data are accurate. A foundation for establishing this type of validity is triangulation (Jick, 1979). Multiple sources of evidence were used including interviews, process mapping, observation, archival data, and brainstorming sessions. Multiple informants were used for different cases. The questions asked in interviews were also grounded in the literature. For example of this, the reader is referred to the description of 'the pipeline survey', which is found earlier in this chapter. Brainstorming sessions held with industry and academic collaborators to triangulate perspectives. Prolonged engagement with field through the industrial secondment also helped the research to become intimately acquainted with the concepts and data.

Tests	Tactic used to improve validity of study
Construct validity	- Multiple sources of evidence were used: interviews, prolonged engagement with field/industrial secondment, process mapping, observation, archival data, brainstorming, - Interview questions and research grounded in the literature - Brainstorming sessions were held with industry and academic collaborators - Progress presentations to industry collaborators - Key industry contacts reviewed case reports and project outputs such as academic papers and presentations. - Interviews were written up and cross checked with interviewees. - Multiple informants were used for different cases - Findings were presented to a range of interviewees outside of the two systems to verify operational measures
Internal validity	- Rival explanations addressed through multiple data analysis techniques including cross case analysis, process maps, interview coding, quantification, descriptive statistics, cluster analysis, brainstorming and cause and effect analysis. - Projects were studied over time with multiple visits to collect data at different points. - Brainstorming sessions were held with industry and academic collaborators
External validity	- Multiple case studies were used: 2 network co-ordinators, 5 projects and 12 pipelines - Evaluation presentations were conducted outside of the cases to establish generalizability to different sectors - Robust case selection criteria for each unit of analysis. - Embedded units of analysis allow for breadth and depth
Reliability	- A case study protocol was developed which includes aims and objectives, sample selection, data collection and analysis methods and interview structure. - The research protocol verified by PhD supervisors, industry collaborators and piloted via an industrial workshop. - A database was collected for each system. This includes a research diary, a folder for each unit of analysis containing any relevant documentation.

Table 4.7: Summary of validity and reliability controls (Source: adapted from Yin, 2003)

Measures to cross check data and model development throughout the research process have been put in place as the research progressed. Key industry contacts reviewed case reports and project outputs, such as academic papers and presentations. Process maps were co-created and cross checked with industry; interviews were written up and emailed to industry for validation. Progress presentations were also regularly delivered to industry and academic collaborators. Finally, the overall findings were examined for construct validity through the evaluation interviews, which were presented to a range of interviewees outside of the two systems to verify operational measures and to ensure that stakeholders outside of the systems of study were able to relate to the concepts in a meaningful way.

4.4.2 Internal validity

Internal validity pertains to establishing a causal relationship, whereby certain conditions are shown to lead to other conditions, as distinguished from spurious relationships. This type of validity has important implications for the cause and effect analyses undertaken in this thesis. Establishing accurate causal relationships has been ensured through a number of techniques. Multiple data analysis techniques have been used, including cross case analysis, process maps, interview coding, quantification, descriptive statistics, cluster analysis, and brainstorming, drawing on both qualitative and quantitative data. Multiple perspectives have been gathered through brainstorming sessions, ensuring that the cause and effect relationships have been reached as a result of a consensus between stakeholders. Projects were studied over time, with multiple visits to collect data at different points. The findings from cause and effect analysis are also related back to theory and relevant studies.

4.4.3 External validity

External validity refers to establishing the domain to which a study's findings can be generalised. The term 'generisability' can be defined as "whether the findings are equally applicable to other research settings, such as other organisations" (Saunders et al., 2007). The research design adopted herein is based on multiple case studies with multiple units of analysis. More specifically it includes 2 network co-ordinators, 5 projects and 12 pipelines across 2 ETO systems. The first tactic to note is the use of embedded units of analysis which account for depth and breadth of analysis. The network co-ordinators allow an in depth 'immersed' investigation of the key organisation within the ETO supply chain. The supplier pipelines allow for focussed data collection which accounts for greater breadth of coverage.

The project unit of analysis provides an intermediate between breadth and depth. A robust case selection criterion was used for each unit of analysis.

The extent to which the findings can be generalised to different sectors is addressed specifically in the evaluation interviews. Evaluation presentations were conducted outside of the cases to establish generalizability to different ETO construction sectors. A case selection criterion was designed to recruit interviewees from a range of ETO construction sectors and a cross section of organisation types. The extent to which findings can be generalised was a particular area of focus for these interviews.

4.4.4 Reliability

The final test is that of reliability. To achieve reliability the study must address the extent to which the operations of a study, such as the data collection procedures, can be repeated with the same results (Yin, 2003).To facilitate reliability, a case study protocol was developed which includes aims and objectives, sample selection, data collection and analysis methods, and interview structure. A more specific protocol was developed from the project and pipeline units of analysis. These research protocols were verified by PhD supervisors, industry collaborators and piloted via an industrial workshop that was held as part of the McCLOSM project. A database was created for each ETO system. This included a research diary, a folder for each unit of analysis within the system containing any relevant documentation.

4.5 SUMMARY

The case research design has been developed in this chapter. The study uses multiple case study design using three embedded units of analysis. Three units of analysis of interest have been specified within an ETO system: the network co-ordinator, projects and supplier pipelines. The case selection criteria have been presented, where 'snowball sampling' plays an important role. A mixed methods research design was also specified, with qualitative methods playing the dominant role and quantitative techniques playing a supporting role. Qualitative and quantitative techniques will be used concurrently.

This chapter has also described the ways in which research methods reviewed in chapter 3 were applied to different units of analysis are described. These individual research methods have been tailored to investigate different units of analysis. This chapter has also described the data analysis techniques used in the study. Multiple data analysis techniques are used including cross case analysis, process maps, interview coding, quantification, description statistics, cluster analysis, brainstorming and cause and effect analysis. Data analysis techniques are also tailored to the units of analysis. Finally, discussions around validity and reliability are addressed. A summary of the tactics used to address four key validity and reliability concerns was presented.

SUMMARY OF CHAPTER 4 AIMS

1. **Introduce the basic case study design and case selection criteria**
   - A multiple case research with embedded units of analysis strategy was specified
2. **Link research questions with research methods**
   - Each research question has been related to bodies of knowledge in the literature and the nature of investigation during the thesis
3. **Identify the units of analysis**
   - Three units of analysis have been specified: network co-ordinators, projects and supplier pipelines. The data collection methods employed for each unit of analysis have been presented along with the data analysis techniques.
4. **Describe the application of research methods to the units of analysis**
   - The research methods for each of the units of analysis have been specified
5. **Explain the tactics used to address validity concerns**
   - The tactics used to improve construct validity, internal validity, external validity and reliability have been discussed

CHAPTER 5

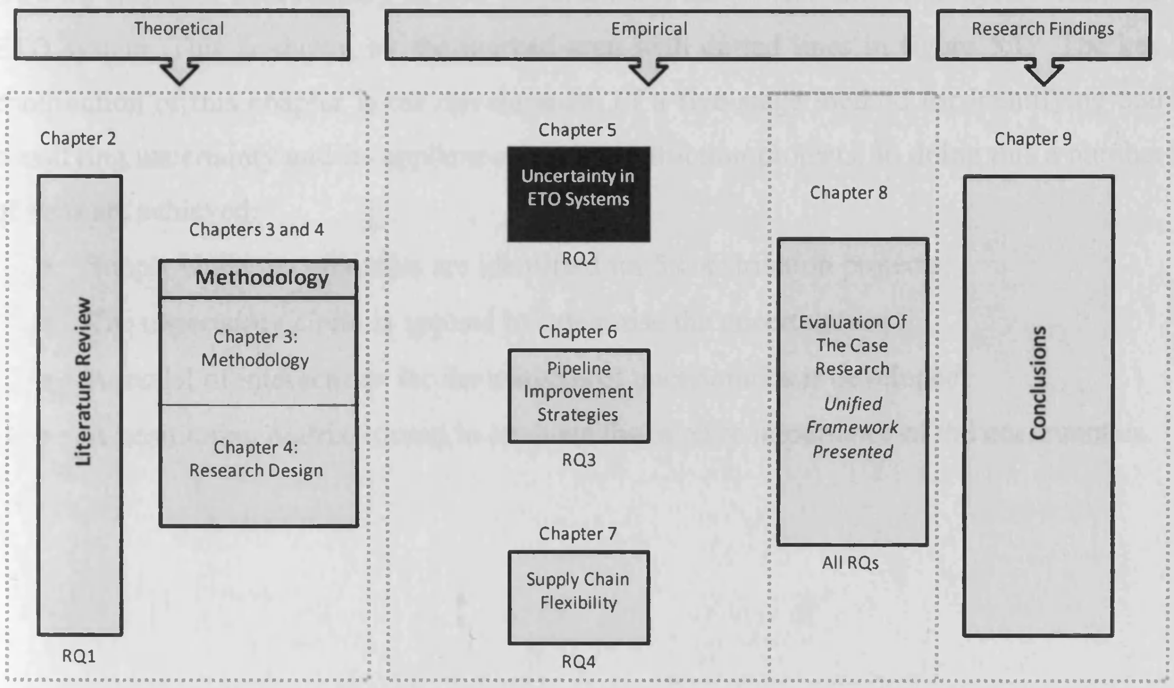
A METHOD FOR IDENTIFYING AND CATEGORISING THE SOURCES OF UNCERTAINTY IN ENGINEER-TO-ORDER SUPPLY CHAINS

CHAPTER 5 AIMS

1) Develop a method for the identification and categorisation of uncertainty in ETO construction supply chains.
2) Apply the method to 5 construction projects

RESEARCH QUESTION ADDRESSED

RQ2: How can the sources of project uncertainty in ETO construction supply chains be identified and categorised?



5. INTRODUCTION

As noted in the literature review, uncertainties affecting supply chain operations are recognized as significant obstacles to achieving value for customers. Mason-Jones and Towill (1998), building on Davis (1993), developed the uncertainty circle model to conceptualise the different sources of uncertainty that affect supply chain performance. This chapter refines this model and applies it to five construction projects. Surprisingly, project uncertainty has received very little attention in the literature. Ward and Chapman (2003) argued that the restricted focus of project risk management must be modified to incorporate an uncertainty management perspective. As noted by Patterson and Neailey (2002), while various authors discuss uncertainty profiles in their work, very little has been written about their development and construction.

The chapter begins with an overview of the projects used in the study, and will primarily draw on empirical data relating to five projects from the project unit of analysis within the ETO system. This is shown by the marked area with dotted lines in figure 5.1. The key contribution of this chapter is the development of a five-stage method for identifying and classifying uncertainty and its application to 5 construction projects. In doing this a number of aims are achieved:

- Supply chain uncertainties are identified for 5 construction projects;
- The uncertainty circle is applied to categorise the uncertainties;
- A model of interactions for the analysis of uncertainties is developed;
- A positioning matrix is used to evaluate the relative importance of the uncertainties.

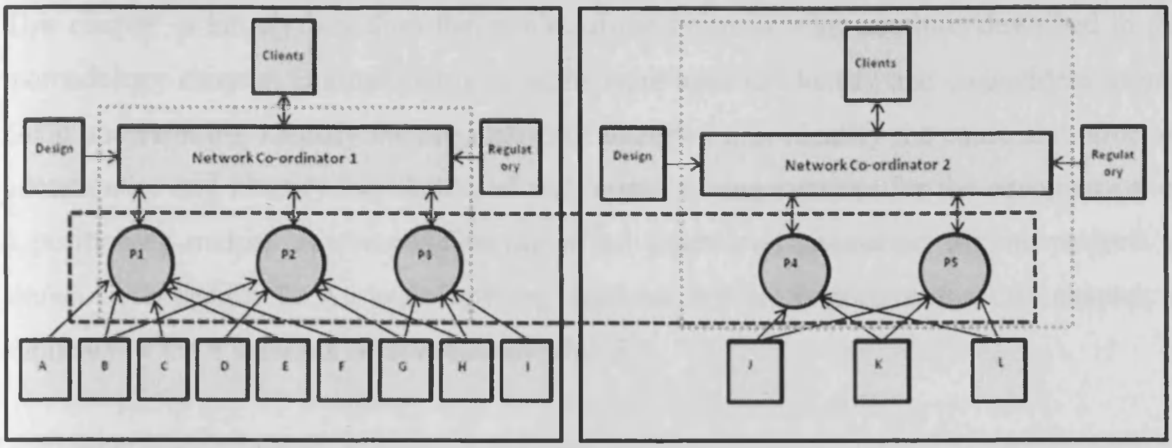


Figure 5.1: The two ETO systems and the primary focus of Chapter 4

5.1 METHOD OVERVIEW

This chapter is primarily concerned with identifying and categorising the uncertainties experienced by the project management teams of five construction projects. The flow of research activities that underpin this chapter are shown in figure 5.2. The first stage is the development of a method for identifying and categorising supply chain uncertainty, based on relevant literature. The method was then applied to 5 construction projects. During the application phase, the first activity was site visits to five different projects along with semi-structured interviews based on the research protocol shown in appendix 3. Using these interviews and site visits, individual project uncertainty profiles were entered on a spreadsheet. These were then coded to create a generic project uncertainty profile for the 5 projects. The generic uncertainty profile was categorised by grouping them by sources of supply chain uncertainty described in Mason-Jones and Towill (1998).

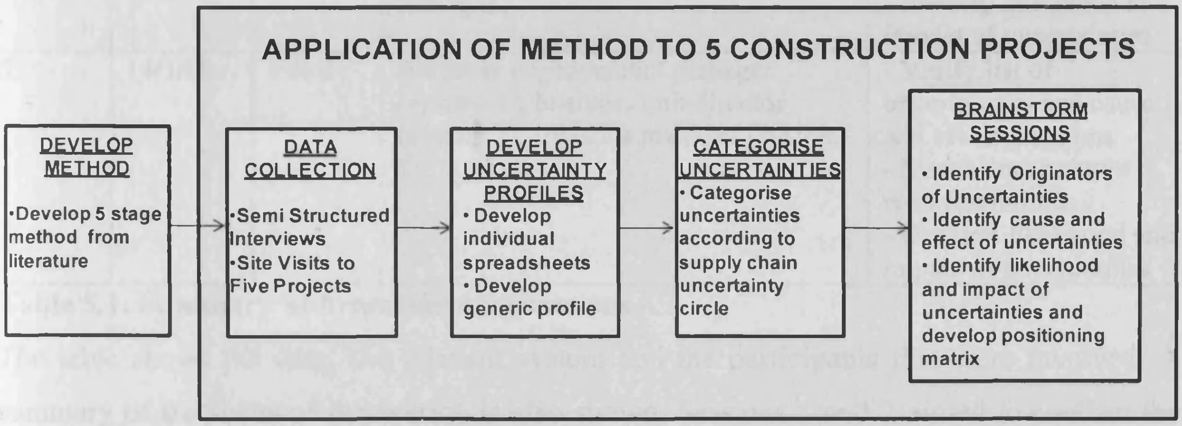


Figure 5.2: Flow of research activities underpinning Chapter 5

This chapter is largely based on the results of the brainstorming sessions described in the methodology chapter. Brainstorming sessions were used to identify and consolidate supply chain uncertainties, identify the originators of uncertainties, identify the cause and effect of uncertainties and identify the likelihood and impact of uncertainties for the development of a positioning matrix. A complete listing of all interviews conducted for the projects is shown in appendix 2. As brainstorming sessions are an important for this chapter, a summary of the 8 sessions is presented in table 5.1.

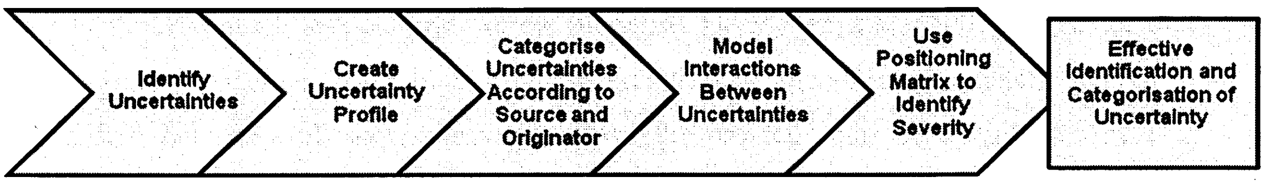
Session	Date	System	Participants	Focus
1	11/7/06	1	Business development team (5 people) and academic collaborator	Develop scope and scale of case study
2	10/11/06	1	Academic collaborator, business improvement manager and supervisor	Develop scope and scale of case study
3	17/4/07	1	Onsite at project 2. Project manager, site manager and foreman.	Identify and consolidate supply chain uncertainties
4	29/5/07	1	Onsite at project 1. Site Team: Site Manager, Project Manager, Quantity Surveyor, Technical Manager.	Identify and consolidate supply chain uncertainties
5	12/1/08	2	Executive meeting for suppliers. Group director, Mechanical and engineering director, business unit director. Representatives of 15 suppliers were present at the training day.	- Identify and consolidate supply chain uncertainties - Cause and effect of uncertainties
6	24/11/08	2	Business unit director and logistics manager.	- Cause and effect of uncertainties - Identify likelihood and impact of uncertainties
7	13/1/09	1	Business improvement manager, supply chain manager, project manager	- Cause and effect of uncertainties - Identify likelihood and impact of uncertainties
8	14/1/09	1 & 2	Business improvement manager (system 1), business unit director (system 2), logistics manager (system 1)	- Verify list of uncertainties and cause and effect diagrams - Match uncertainties with flexibilities - Confirm likelihood and impact of uncertainties

Table 5.1: Summary of brainstorming sessions

The table shows the date, the relevant system and the participants that were involved. A summary of the focus of the session is also shown. Sessions 1 and 2 aimed to confirm the scope, scale and focus of the research. Sessions 3, 4 and 5 aimed to identify and consolidate supply chain uncertainties. The spreadsheets for different projects, as well as the generic uncertainty profile were discussed in these sessions. Sessions 5, 6 and 7 investigated the cause and effect of uncertainties. A 'post-it-note' exercise was undertaken, whereby uncertainties and their relationships were established by the group by writing, moving and agreeing on the position of post it notes showing the cause and effect of uncertainties. This is a popular technique used in lean process mapping (Hines et al., 1998; Hines and Taylor, 2000). Sessions 6, 7 and 8 sought to identify the likelihood and impact of uncertainties. Post it notes, with the generic supply chain uncertainties written on them, were added to a large board with the axis impact, running from high to low, and 'likelihood', showing high to low. These sessions aimed to bring consensus on the positioning of these uncertainties relating to likelihood and impact. These brainstorming sessions were used to create a cause and effect diagram for the supply chain uncertainties, along with an assessment of the impact and likelihood of the different uncertainties.

5.2 A METHOD FOR IDENTIFYING AND CATEGORIZING UNCERTAINTY

In order to guide this chapter, a method for identifying and categorizing uncertainty is proposed. This is shown in figure 5.3, and is developed throughout the remainder of this section. The rest of chapter examines how the method may be applied to a group of projects.



5.3 Method for identifying and categorising supply chain uncertainty

Step 1 - Identify uncertainties

The first step in the method is the identification of uncertainty. van der Vost and Beulens (2002) argued that in order to identify effective supply chain redesign strategies, one should focus on the identification and management of uncertainties in the decision making processes that hinder optimal performance. Using a qualitative methodology, they argued it is possible to identify uncertain scenarios. Ward and Chapman (2003) proposed that uncertainty management requires the identification of all the many sources of uncertainty which give rise to and shape our perceptions of threats and opportunities. Books aimed at practitioners provide some useful guidelines for possible ways to identify uncertainties. For example, the Institution of Civil Engineers (1998) suggested that risk and uncertainty is best identified through teams of stakeholders analyzing the whole life of an investment, using such aids as site visits, check lists of problems, information from similar investments and projects, case studies, safety reviews and impact studies, reviews of plans, designs and key documentation.

Step 2 – Create an uncertainty profile

The next step is to compile an uncertainty profile. According to Williams (1994), a project risk register should be a list of adverse events that might occur, and is likely to include information on impact and risk reducing actions. It acts as a repository of knowledge and initiates the analysis and plans that follow from it. The risk register is an effective tool to enable a project team to evaluate the risks as part of the decision making process and enables risk reduction and mitigation plans (Patterson and Neailey, 2002). Ward (1999) suggested that the risk register enables the documentation of the sources of risk and their responses, as well as their classification and involves compiling a log, list or register. However, as noted by Patterson and Neailey (2002), while various authors discuss risk registers in their work, very little has been written about their development and construction. Project uncertainty profiling is based on similar principles to the risk register, but has received much less attention in the literature. De Meyer et al. (2002) suggested that an uncertainty profile is a qualitative characterization of uncertainties, and the degree to which different types of uncertainty may affect the project. This uncertainty profile is a subjective estimate and indicates which uncertainty types are the most important. To help identify the dominant uncertainty types, a team may use experiences gained from previous projects, or they may adopt more formal approaches such as statistical analyses, technology and market forecasts, scenario planning and creativity management techniques.

Step 3 - Categorize according to source of supply chain uncertainty and originator

Once the sources of uncertainty have been identified and profiled, Ward and Chapman (2003) argued that it is useful to explore, understand and categorize the origins of project uncertainty before seeking to manage it. As described in the literature review and methodology chapters, the uncertainty circle can be used to classify uncertainties in the supply chain, which includes demand, supply, process and control sources of uncertainty (Childerhouse and Towill, 2004; Mason-Jones and Towill, 1998; Sanchez-Rodrigues et al., 2008).

Step 4 – Establish model of interactions for uncertainties

The importance of establishing cause and effect was highlighted in the literature review (Aguayo, 1991; Bicheno, 2006; Sterman, 1989). This logic was applied to the method for identifying and categorising uncertainty. Identifying the interactions between uncertainties will enable project managers and supply chain managers to understand the root cause of the uncertainties that they face. In this chapter, cause and effect techniques are modified to show the interactions between uncertainties using the uncertainty circle as a framework.

Step 5 - Use a positioning matrix to establish the relative importance

Early research highlighted the importance of establishing probabilities and cost and time scenarios for different risks (Chapman, 1979). Williams (1996) suggested that two key dimensions of risk are likelihood, which is the probability of an undesirable occurrence, and impact, which is the seriousness and scale on other activities. Cost and time are key elements of the impact (The Institution of Civil Engineers, 1998). The multiplication of likelihood by impact pervades the risk management literature (Baccarini and Archer, 2001; Williams, 1996), and faciklitates the development of a ranked list. An important associated technique is the Likelihood–Impact Matrix, where the probability and impacts of each uncertainty are assessed against defined scales, and plotted on a two-dimensional grid. The position on the matrix offers an indication of the relative significance of the risk (Hillson, 2002).

5.2 INDIVIDUAL PROJECT PROFILES

The section offers an overview of each of the projects in the two systems. An individual uncertainty profile has been developed for each project, which are presented in the rest of this section.

5.2.1 Projects in engineer-to-order system 1

Project 1

This project consisted of the design and build of 32 units comprising 24 flats and 8 affordable dwellings. The 3 storey scheme included commercial units on the ground floor and a basement car park. Space on the site was very limited, as the footprint of the building covered the entire site. Therefore, careful planning was required to make sure that access to the site was kept clear at all times. The site is based in London. Much of the frame of the building was made up from pre-cast concrete, which required large volumes of pre-cast concrete deliveries. The contract type was a 'design and build' contract. The supplier pipelines in the system that are involved in this project are the elevator pipeline (case A), windows (case B), pre-cast concrete (case C), a metalwork subcontractor (case E), and a brick and block supplier (case F). The project was completed in August 2007. The main uncertainties for project 1 are shown in table 5.2.

Uncertainties for Project 1
Cost uncertainty. Meeting the cost constraints of a low budget project was a consistent challenge throughout the project.
Permissions and project milestones. Getting permissions from local council for services took a long time and was time consuming. This put pressure on meeting project milestones.
Resource and workflow. Synchronising resource requirements with the workflow. In particular, matching labour resources to timber frame erection and deliveries was challenging (delivered at 4 hour intervals).
Access. Securing access for regular deliveries of timber frame in a city centre location was difficult.
Capacity of subcontractors. Towards the end of the project the main contractor was offered some extra work extending the original project. Some of the suppliers and subcontractors could respond to these requirements, others did not have the capacity to take on extra work.
Equipment. Uncertainty over availability of equipment, such as urban articulated trailers and tower cranes.
Information exchange and decision making. Slow information exchange between client, designers and suppliers made decision making difficult.
Design approvals and project milestones. Long lead-times for feedback on designs put pressure on the project plan.
Late changes in specification. The client awarded the main contractor an extension phase, adding to the original project. Information for the new phase was very late and difficult to accommodate.
Labour. Difficult to get flexible labour to match upswings and downswings in workflow.

Table 5.2 Uncertainties experienced in project 1

Project 2

Project 2 was a development of 37 flats for a social housing developer in Greater London. The building was designed using a timber frame system construction. The contract type for this project was also a 'design and build'. Cost was a key driver for this project with a small project value of £3.2 million, and the site was adjacent to 2 schools, making it important to liaise with the local community throughout the build. The supplier pipelines investigated in this project were windows (case B) and timber frame systems (case G). The project was completed in January 2007. The main uncertainties for project 2 are shown in table 5.3.

Uncertainties for Project 2
Access and impact on community. Maintaining access for local businesses, and deliveries made to these businesses, situated within and behind the site was challenging throughout the project. This created further uncertainty for relating to access points and work area management on site.
Storage space and deliveries. Tight storage space constraints led to the need for small, frequent and timely deliveries. Suppliers were not always able to meet these requirements.
Permissions. Lack of information from planners regarding permissions led to problems setting up services for the site. As a result, work started on site with no services.
Access, workflow and community impact. Large volumes of pre-cast concrete had to be delivered into a busy London location. Due to access constraints these deliveries would often lead to the blocking of traffic routes, causing traffic and workflow problems.
Equipment. Uncertainty over availability of desired equipment.
Accuracy of project plan. Timings and resource requirements for the critical chain (mostly related to pre-cast concrete deliveries) had to be revised frequently.
Geology. Abnormal features of site were encountered, which could not have been foreseen. Underground infrastructure, such as sewage and pipelines, caused early delays in the project.
Information exchange. Co-ordinating timely and correct information from clients and consultants.
Shared objectives. The project combines private and public housing. Mixing public and private interests can lead to conflicting priorities.
Weather. Excessive rain during the summer led to unexpected delays

Table 5.3: Uncertainties experienced in project 2

Project 3

Project three was a regeneration project and is for a consortium of clients. The scheme included refurbishment of 325 houses with new external works, playgrounds, footpaths and landscaping. In addition, the scheme included 442 new homes, three commercial units and a community building, with accommodation for a library and a housing office managed across ten separate sites. The overall contract value was around £66m, with refurbishment works due to be completed in 36 months and the new build development site in 60 months. This project was managed on a private finance initiative basis, where public and private organisations worked together to deliver the project. This involves private sector provision of capital asset and services with the public sector acting as the main purchaser or enabler of the project. This project included a consortium of developers and housing associations. The supplier pipelines investigated in this project were timber frame systems (case G), doors (case H) and timber (case I). The project was due to be completed in March 2012. The main uncertainties for project 3 are shown in table 5.4.

Uncertainties for Project 3
Scheme viability. Finding the appropriate balance between regeneration, new build, flats and houses.
Late changes to specification. A late decision regarding whether or not the existing commercial centre be moved out or not led to a lot of changes to the original plans.
Shared objectives. Maintaining good relationships, and building a common understanding, between private and public organisations.
Fragmented decision making. Nobody made decisions about tolerances in the original designs.
Rigid design. Not enough tolerance was built into the design to allow for variability in the construction process.
Supplier bankruptcy. Uncertainty over subcontractors and suppliers going out of business. This became more acute as the 'credit crunch' recession of 2008/2009 unfolded.
Deliveries. Suppliers and transport companies faced uncertainty over which phase of the site to deliver to. Deliveries were frequently made to the wrong site/phase of the project.
Weather and Impact on local community. Bad weather, and movement between multiple sites, made it difficult to keep roads and sites clear from mud.
Impact on local community. The impact of multiple sites in a residential area caused traffic management problems, especially near schools.
Security. Security issues were prevalent across multiple sites and phases.

Table 5.4: Uncertainties experienced in project 3

5.2.2 Projects in engineer-to-order system 2

Project 4

Project four was a twenty storey commercial tower in the City of London creating 586,000 square feet of office space. The building was designed for professional and financial services occupiers and provides two trading floors at the lower level, with a variety of floor plates above. The scheme also included over 50,000 square feet of planted roof terraces. The project was delivered on a construction management contract by the network co-ordinator in system 2. The project was delivered over approximately 3 years for a private client. A key design feature was a three tier glass façade. The core of the building was constructed using the slipform method, where the formwork and attached working platforms are slowly moved up using hydraulic jacks so that the system slides up continuously throughout the day. The supplier pipelines investigated in this project were those of a paint subcontractor (case J), modular bathroom supplier (case K) and a dry-lining subcontractor (case L). Construction of the project was completed in May 2009. The main uncertainties for project 4 are shown in table 5.5.

Uncertainties for Project 4
Scheme viability and Market conditions. Uncertainty over the extent to which demand for office space will remain strong during the recession.
Access and Deliveries. Getting frequent deliveries of materials into the City of London, which is located in a congestion charge zone.
Project team and Shared objectives. Managing and co-ordinating the large numbers of organisations required for such a complex project.
Permissions and Workflow. Local authority and planning permissions dictated that the slip-form operations could not work continuously and had to finish by 6pm due to noise regulations. This constrained the effectiveness of shift working in the project.
Supplier failure/ bankruptcy. Uncertainty over subcontractors and suppliers going out of business. This became more acute as the 'credit crunch' recession of 2008/2009 unfolded.
Access. Very difficult to get the volume of deliveries required for the site into the limited access point. It was also difficult to manage the queues of lorries around the site.
Cost. The network co-ordinator is responsible for meeting a fixed price contract for the client.
Meeting project milestones. Noise regulation thresholds constrained overtime hours, meaning that any delays were difficult to make up.
Safety. Scope of project and height of structure called for rigorous safety procedures.
Sourcing. Uncertainty over sourcing and delivery of specialist materials and building elements

Table 5.5: Uncertainties experienced in project 4

Project 5

Project five was a six storey office block in an exclusive part of central London creating 100,000 square feet of office space. As with project one, the construction method relied on pre-cast concrete for the frame of the building. The scheme included six floors and a basement. The finish of the building is of a very high standard with a Portland stone and

Indian granite façade and award winning artistic sculptures adorning the building. The design also included a large atrium structure at the centre of the building. Strict grading regulations applied to the building, which had to conform to the historic surroundings. The project was a construction management contract to be delivered over approximately 2 years for a private client. The supplier pipelines investigated in this project were those of a paint subcontractor (case J), modular bathroom manufacturer (case K) and a dry-lining subcontractor (case L). The main uncertainties for project 5 are shown in table 5.6.

Uncertainties for Project 5
Quality. Meeting high quality and specification requirements for the client was a challenge throughout the project.
Late changes to specification. Due the high quality specification of the project, the client was very particular about the detail in the design process and introduced a number of changes during the build.
New technology or technique. The scheme involved innovative design features (e.g. the use of artistic sculptures and architectural art throughout the building) which required new approaches to be developed.
Permissions. Heritage and grading organisations had to be consulted at each step of the design process to ensure that the project conformed to their requirements.
Effectiveness of contractual arrangements. The client wished to change contractual terms after the project had started.
Access. Access points to the site were very restricted, especially for larger vehicles.
Work areas and storage space. Storage areas and working areas were very restricted. A number of 'workshop areas' had to be set up to manage the flow of materials and to perform various works.
Scheme viability and Market conditions. Uncertainty over the extent to which demand for office space will remain strong during the recession.
Sourcing and Deliveries. Uncertainty over sourcing and delivery of specialist materials and building elements.
Cost and Meeting project milestones. The network co-ordinator is responsible for meeting a fixed price contract for the client.

Table 5.6: Uncertainties experienced in project 5

5.3 SYSTEM UNCERTAINTIES

5.3.1 Uncertainties in system 1

Table 4.7 shows the uncertainties that are experienced across the 3 projects in system 1. It highlights the uncertainties that apply to individual projects and those that were experienced across projects. Projects 1 and 2 shared uncertainties relating to permissions, volatility of workflow, access issues, equipment and information exchange. Projects 2 and 3 shared uncertainties relating to deliveries, impact on the community, shared objectives and the weather. Projects 1 and 3 both experienced uncertainties relating to late changes in specification and fragmented decision making.

<table>
<tr><th colspan="3">System 1</th></tr>
<tr><th>Project 1</th><th>Project 2</th><th>Project 3</th></tr>
<tr><td>Cost</td><td></td><td></td></tr>
<tr><td>Design approvals</td><td></td><td></td></tr>
<tr><td>Labour</td><td></td><td></td></tr>
<tr><td>Meeting project milestones</td><td></td><td></td></tr>
<tr><td>Capacity of subcontractors</td><td></td><td></td></tr>
<tr><td>Resource</td><td></td><td></td></tr>
<tr><td></td><td>Storage space</td><td></td></tr>
<tr><td></td><td>Accuracy of project plan</td><td></td></tr>
<tr><td></td><td>Geology</td><td></td></tr>
<tr><td></td><td></td><td>Scheme viability</td></tr>
<tr><td></td><td></td><td>Rigid design</td></tr>
<tr><td></td><td></td><td>Security</td></tr>
<tr><td></td><td></td><td>Supplier bankruptcy</td></tr>
<tr><td>Fragmented Decision Making</td><td></td><td>Fragmented decision making</td></tr>
<tr><td>Late changes in specification</td><td></td><td>Late changes in specification</td></tr>
<tr><td></td><td colspan="2">Deliveries</td></tr>
<tr><td></td><td colspan="2">Impact on community</td></tr>
<tr><td></td><td colspan="2">Shared objectives</td></tr>
<tr><td></td><td colspan="2">Weather</td></tr>
<tr><td colspan="2">Permissions</td><td></td></tr>
<tr><td colspan="2">Workflow</td><td></td></tr>
<tr><td colspan="2">Access</td><td></td></tr>
<tr><td colspan="2">Equipment</td><td></td></tr>
<tr><td colspan="2">Information exchange</td><td></td></tr>
</table>

Table 5.7: Uncertainties in system 1

5.3.2 Uncertainties in System 2

Table 5.8 presents the uncertainties that were experienced across the 2 projects in system 2. It also shows the uncertainties that applied to individual projects and those that were experienced across projects 4 and 5. Projects 4 and 5 both experienced uncertainty relating to access, sourcing, deliveries, scheme viability, market conditions, cost, meeting project milestones and permissions.

<table>
<tr><th colspan="2">System 2</th></tr>
<tr><th>Project 4</th><th>Project 5</th></tr>
<tr><td>Safety</td><td rowspan="5"></td></tr>
<tr><td>Supplier failure/ bankruptcy</td></tr>
<tr><td>Project team</td></tr>
<tr><td>Shared objectives</td></tr>
<tr><td>Workflow</td></tr>
<tr><td rowspan="5"></td><td>Quality</td></tr>
<tr><td>Late changes to specification</td></tr>
<tr><td>New technology or technique</td></tr>
<tr><td>Effectiveness of contractual arrangements</td></tr>
<tr><td>Work areas and storage space</td></tr>
<tr><td colspan="2">Access</td></tr>
<tr><td colspan="2">Sourcing</td></tr>
<tr><td colspan="2">Deliveries</td></tr>
<tr><td colspan="2">Scheme viability</td></tr>
<tr><td colspan="2">Market conditions</td></tr>
<tr><td colspan="2">Cost</td></tr>
<tr><td colspan="2">Meeting project milestones</td></tr>
<tr><td colspan="2">Permissions</td></tr>
</table>

Table 5.8: Uncertainties in system 2

5.3.3 Similarities and differences between the two systems

The previous 2 sections have shown that there are uncertainties that are unique to individual projects and those that are shared between projects. A summary of these similarities and differences is shown in table 5.9. This section shows the uncertainties that are unique to the different systems and those that are shared across the two systems.

The uncertainties experienced in both systems included supplier failure and bankruptcy, shared objectives, workflow volatility, late changes to specification, storage pace, access, deliveries, scheme viability, cost, meeting project milestones and permissions. Uncertainties experienced in system 1 included design approvals, labour, capacity of subcontractors, resource, security, rigid design, geology, accuracy of project plan, impact on community, weather, equipment and information exchange. Uncertainties experienced in system 2 include safety, project team, quality, new technology or technique, work areas, sourcing, deliveries and market conditions.

Uncertainties experienced in both systems	Uncertainties in System 1 only	Uncertainties in System 2 only
Supplier failure/bankruptcy	Design approvals	Safety
Shared objectives	Labour	Project team
Workflow	Capacity of subcontractors	Quality
Late changes to specification	Resource	New technology or technique
Storage space	Security	Work areas
Access	Rigid design	Sourcing
Deliveries	Geology	Deliveries
Scheme viability	Accuracy of project plan	Market conditions
Cost	Impact on community	
Meeting project milestones	Weather	
Permissions	Equipment	
	Information exchange	

Table 5.9: Differences and similarities between system uncertainties

5.4 CATEGORISING SUPPLY CHAIN UNCERTAINTY

Figure 5.4 provides a summary of the sources of supply chain uncertainty. The uncertainties have been categorized according to the different sources of supply chain uncertainty: control, demand, process, and supply. The figure shows 39 uncertainties with 9 control uncertainties, 7 demand, 16 process and 7 supply uncertainties. A further 3 external uncertainties were identified as beyond the boundaries of the system. These external uncertainties were identified as market conditions, unforeseen geology or site conditions and the weather. Forty two uncertainties were identified in total. The largest source of supply chain uncertainty was process uncertainty, which accounts for 16 of the 42 uncertainties.

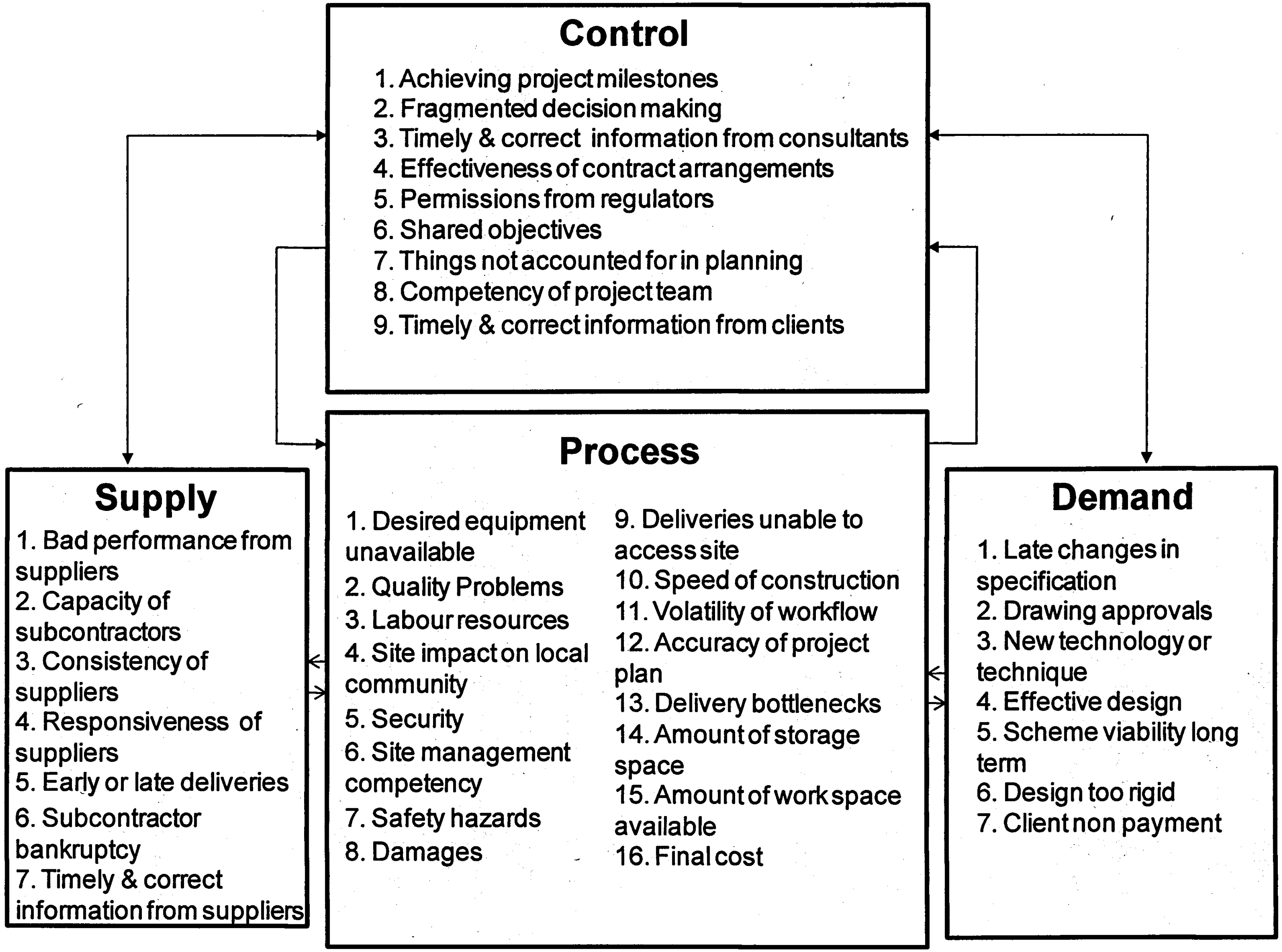


Figure 5.4: The sources of uncertainty in ETO construction supply chains

The categorisation of uncertainties in figure 5.4 also highlights the interconnectivity between different sources of uncertainty. Demand, process, supply and control uncertainties were intimately related. For example, a network co-ordinator may contribute to early or late deliveries by not passing on required information to suppliers or ordering materials early enough. Demand uncertainty, such as client non payment may filter down the supply chain and result in a supplier bankruptcy.

It shows that control uncertainties relate primarily to information exchange, team working structures and project management. Demand uncertainty is exacerbated by unique requirements for individual projects and a fragmented design process, where external design consultants such as architects and structural engineers liaise with clients, main contractors and suppliers to reach a decision of final specifications. Major demand uncertainties also refer to the extent to which the scheme will be viable long term.

Process uncertainty refers primarily to those uncertainties experienced during on site, such as equipment failure or the volatility of workflow. Supply uncertainties result from poorly performing suppliers. This may take the form of early or late deliveries, inconsistent lead times or supplier financial failure. Suppliers and subcontractors are the main originators of these uncertainties, but the network coordinator may also contribute to some of these uncertainties. External uncertainties are those that originate outside of the ETO system. These may take the form of inclement weather conditions that delay site progress or unforeseen geology or underground characteristics, such as underground sewage works or archaeological finds.

A full listing of the generic uncertainty profile for all projects is shown in Table 5.10. It shows the generic uncertainty, the source of supply chain uncertainty, and the originator of the uncertainty. The originators were identified as clients, designers/architects, network co-ordinators, suppliers and regulators. Some of the uncertainties have multiple originators. The external uncertainties also have uncertainties that originate outside of the system.

Uncertainty	Supply Chain Uncertainty Type	Client	Architect	Network Coordinator	Supplier	Regulator
Timely/correct information from clients	Control	X				
Timely/correct information from consultants	Control		X			
Fragmented decision making	Control	X	X	X	X	X
Permissions from regulators	Control					X
Effectiveness of contractual arrangements	Control	X		X		
Shared objectives	Control	X		X		
Competency of project team	Control	X		X		
Achieving project milestones	Control			X		
Things not accounted for in planning	Control	X	X	X		
Client non payment	Demand	X				
Appropriate or effective design for scheme	Demand	X	X			
Late changes in specification	Demand	X	X			
Drawing approvals	Demand	X	X			
New technology or technique	Demand	X	X	X	X	X
Scheme viability long term	Demand	X				
Design too rigid to accommodate change	Demand		X			
Economic market conditions	External					
Weather	External					
Geology/site characteristics	External					
Cost	Process	X	X	X	X	X
Desired equipment unavailable	Process			X	X	
Accuracy of project plan	Process			X		
Quality/Excessive snagging	Process			X	X	
Labour resources	Process			X	X	
Competency of site management	Process			X		
Deliveries unable to access site	Process			X		
Delivery bottlenecks	Process			X		
Amount of storage space available	Process			X		
Amount of work space available	Process			X		
Site impact on local community	Process	X	X	X	X	X
Speed of construction	Process			X		
Volatility of workflow	Process			X		
Safety hazards	Process			X		
Security	Process			X		
Damages	Process			X		
Timely and correct information from suppliers	Supply				X	
Early or late deliveries	Supply			X	X	
Subcontractor bankruptcy	Supply				X	
Bad performance from suppliers	Supply			X	X	
Capacity of subcontractors	Supply				X	
Consistency of suppliers	Supply					
Responsiveness of suppliers	Supply				X	

Table 5.10: Generic uncertainty profile

Table 5.11 provides a summary of the uncertainty profile. The uncertainties have been categorized according to the different sources of supply chain uncertainty: control, demand, process supply and external. It also shows a summary of the originators of these uncertainties. The summary table shows that the largest source of supply chain uncertainty is process uncertainty, which accounts for 16 of the 42 uncertainties. 23 of the 41 uncertainties were also identified as having the network co-ordinator as the sole or joint originator of the uncertainty. Regulators were the originators of the least uncertainties and were the sole or joint originator of 5 uncertainties.

Supply Chain Uncertainty	Number of Uncertainties Identified	Client	Architect	Network Coordinator	Supplier	Regulator
Control	9	6	3	6	1	2
Demand	7	6	5	1	1	1
Process	16	2	2	16	5	2
Supply	7	0	0	2	7	0
External	3	0	0	0	0	0
Total	42	14	10	23	14	5

Table 4.11: Summary of supply chain uncertainties and their originators

As can be seen from table 5.11, the client and main contractor are the most frequent originators of control uncertainties. Demand uncertainty is exacerbated by the unique requirements for each individual project, and, also by a fragmented design process, where external design consultants such as architects and structural engineers liaise with clients, main contractors and suppliers to reach a decision of final specifications. Major demand uncertainties also refer to the extent to which the scheme will be viable long term. Table 5.11 shows that the client and the architect are the major originators of these demand uncertainties.

Process uncertainty refers primarily to those uncertainties experienced during site construction phase, such as equipment failure or the volatility of workflow. Table 5.11 highlights that the network co-ordinator contributes most to these uncertainties. Supply uncertainties result from poorly performing suppliers. This may take the form of early or late deliveries, inconsistent lead times or supplier financial failure. Suppliers and subcontractors are the main originators of these uncertainties, but the network coordinator may also contribute to some of these uncertainties. For example, a network co-ordinator may contribute to early or late deliveries by not passing on required information, or by not ordering materials early enough. External uncertainties are those that originate outside of the ETO system. These may take the form of inclement weather conditions that delay site progress, or unforeseen geology, or underground characteristics such as underground sewage works or archaeological finds.

5.5 MODELLING THE INTERACTIONS BETWEEN UNCERTAINTIES

A cause and effect diagram, based on the sources of supply chain uncertainty, is shown in figure 5.5. This investigates the causes and interactions between some of the uncertainties developed in the profile. The uncertainty circle shows that site processes, and their interaction with the supply and demand side, are directed by the control system. The supply chain uncertainty circle captures the interrelationships between different uncertainties and between different parts of the supply chain. The network coordinator responds to the immediate customer, which in this case is the client, with a design process facilitated by design consultants. Required materials, equipment and labour are replenished by various subcontractors and suppliers from the supply side. The potential outputs of these uncertainties are time overruns, cost overruns, quality defects, a poor safety record and a building 'unfit for purpose'.

The causes identified for each uncertainty source are discussed below. Relevant literature is referred to for the different causes in order to highlight the link with different bodies of knowledge and further explain the different causes.

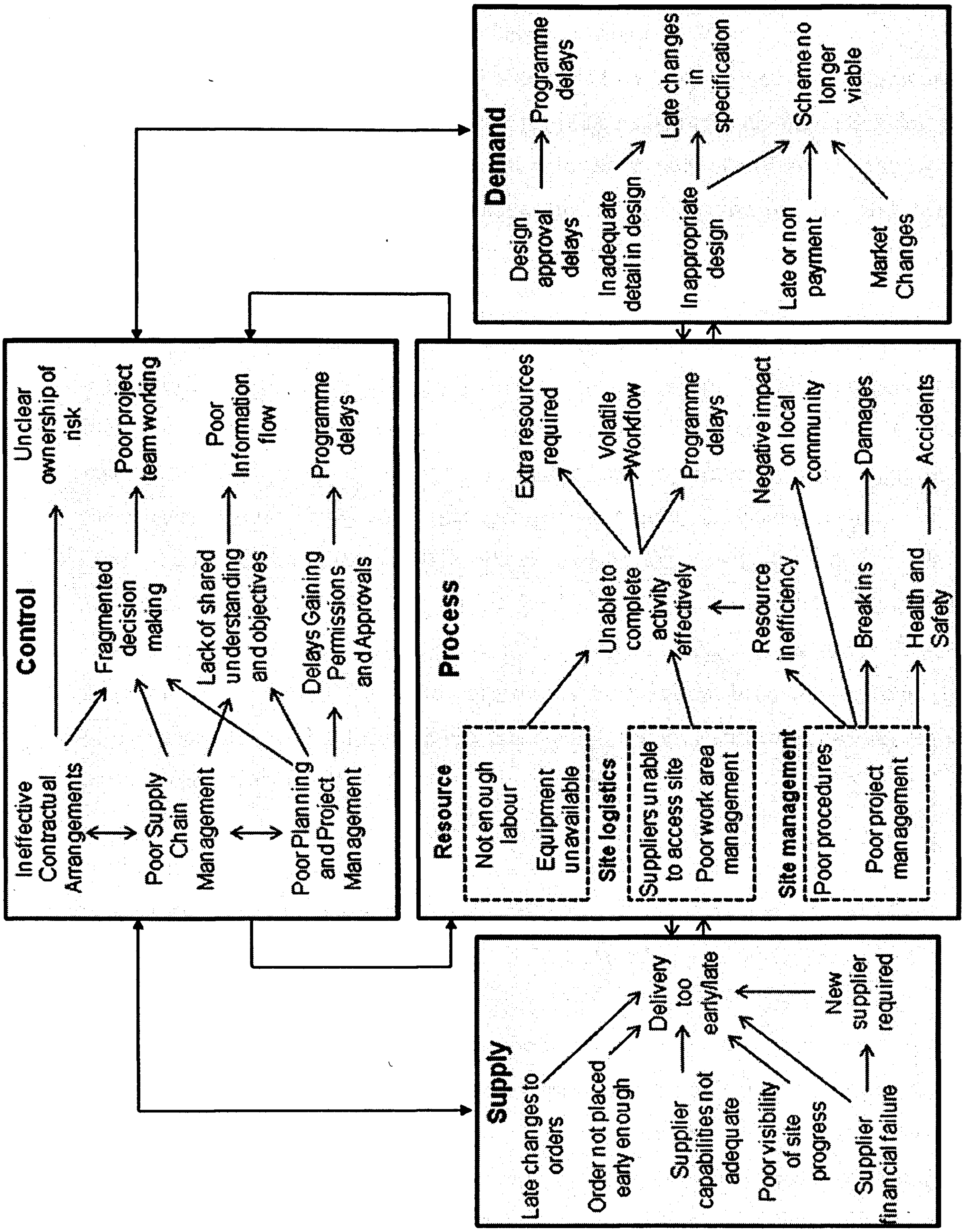


Figure 5.5: Cause and effect diagram for engineer-to-order construction uncertainties

The causes of control uncertainties result in, among other negative impacts, poor project team working for the project coalition and an unclear ownership of risk. Control uncertainties in the ETO systems are caused by the following:

- *Ineffective contractual arrangements*. Many authors have argued that contractual arrangements are a critical success factor for projects (Chua et al., 1999; Sanvido et al., 1992). The literature in this area refers to the importance of getting the right contract type, the allocation and management of risk, setting realistic and clear objectives (Gordon, 1994), as well as the provision of a formal resolution process to resolve disputes (Diekmann and Girard, 1995).
- *Poor supply chain management*. The consequences of poor supply chain management have been widely addressed in the supply chain management literature, across a range of sectors and industries (Christopher, 2005). In the construction industry there are specific studies and government reports exploring the dangers of poor supply chain management and arguing for change (Dainty et al., 2001a; Egan, 1998; Latham, 1994; Vrijhoef and Koskela, 2000).
- *Poor planning and project management*. Zwikael and Globerson (2006) found that an effective project plan was the most frequently quoted success factor in the literature they reviewed. Successful project management has been defined in terms of the successful accomplishment of time, quality, resource and cost objectives of a project (Baccarini, 1999).

A combination of process uncertainty causes on site can result in an inability to complete an activity effectively. The root causes are:

- *Inadequate resources*. This refers to the lack of availability of labour, equipment, or materials to complete an activity.
- *Poor site logistics*. If suppliers and subcontractors are unable to access the site at the right time then the ability to complete a task may be affected. Poor work area management could also lead to delays if the work area is not free and accessible when work is scheduled to start. Agapiou et al. (1998a) propose that major productivity gains are possible by improving site logistics and material flow. They find that improvements in logistics processes reduce costs by 5%.

- *Poor site management.* Poor procedures, such as poor security protocols, poor health and safety and poor community engagement processes, will increase the risk of accidents and break-ins and have a negative impact on the local community. This is consistent with Chan and Kumaraswamy (1997) who found that one of the five principal causes of project delays is ineffective site management and supervision.

The causes of supply uncertainty result in either an untimely delivery or, possibly, a new supplier being required. The causes are:

- *Supplier financial failure.* Supplier financial problems may range from 'chains of credit' from further up the supply chain (from the demand side) or from failures further down the down the supply chain (from a supplier's supplier). These problems agree with the findings in chapter 6. The results could range from late deliveries to a complete inability to supply. The recession at the time of writing has made this seem more likely. On one of the projects visited during this study a façade supplier went into administration.
- *Inadequate supplier capabilities.* Suppliers' capacities and capabilities are identified as a root cause of supply uncertainty. Naim and Barlow (2002) recognized the 'inability to rapidly reconfigure' as a hot spot in their analysis of house-building supply chains. Subcontractors were selected by headquarters, but are called on as and when required by the site without medium term planning horizons. Subcontractors and suppliers therefore commit themselves to a number of different sites without actually having the capabilities or capacity to do so.
- *Poor visibility of site progress.* Suppliers are often unable to gain up to date information on site progress and cannot, therefore, attain visibility of delays or early requirements for deliveries. This problem is also highlighted in chapter 6 of this thesis. The importance of transparency and visibility of progress on project sites has been discussed by Formoso et al. (2002).
- *Orders not placed in time.* This concurs with Naim and Barlow (2003), who highlighted the lack of market knowledge in making purchasing decisions as a 'hot spot'. Time scales for buying and calling off materials are often not properly established and suppliers have little visibility of long term requirements.

- *Late changes to orders*. Late changes originating from the demand side can cause problems for the supply side. In the study conducted by Chan and Kumaraswamy (1997) another of the five principal causes of project delays is client initiated variations.

Demand uncertainties can lead to programme delays, late changes in specification and an unviable scheme. The sources of these are:

- *Inadequate or inappropriate designs*. The most severe outcome of this uncertainty is that the scheme is no longer deemed viable and must be terminated. A less severe outcome is that there are late changes in project specification as the project progresses. An in depth study of the effect on a system of changes to orders is provided by Williams and Eden (1995). Their systems dynamics analysis suggests that design changes can add 22% to project cost.
- *Delays approving designs*. The problems associated with design approval have been well documented in the literature (Barker et al., 2004; Williams and Eden, 1995). Barker et al. (2004) found that information exchange at the design stage was one of the major concerns in programme development.
- *Financial problems*. Dainty et al. (2001a) suggested that even legislation within the 1998 Construction Act had failed to ensure on time payments to subcontractors or to prevent companies from withholding retention payments at the end of contracts. Such practices lead to cash flow difficulties throughout the supply chain.
- *Market Changes*. At the current time of writing market changes have had a huge impact on market demand across a range of sectors, making tenants and buyers for buildings difficult to find and significantly reducing the number of commercial projects being initiated in the marketplace.

5.5 USING A POSITIONING MATRIX TO EVALUATING PROJECT UNCERTANTIES

This section investigates the relative importance of different uncertainties. It establishes the likelihood of different uncertainties developing into a negative outcome and the potential impact in terms of cost and time penalties. These two dimensions, which are well documented in the risk management literature (Patterson and Neailey, 2002; Willams, 1994), are used here to indicate the relative importance of the different uncertainties. As previously described, a brainstorming activity was conducted and uncertainties identified in table 5.11 were plotted on a graph with the axes 'impact' and 'likelihood'. Gridlines were then placed on the graph to enable numerical values to be allocated to uncertainties. The positioning matrix is shown in figure 5.6.

As can be seen by the clustering in the positioning matrix, control uncertainties have the highest importance rating with an average per uncertainty of 6.5. Demand uncertainties average 5.2 per uncertainty, with supply uncertainties averaging 3.4. Process uncertainties average 3.1, with external uncertainties averaging 2.1.

5.6 DISCUSSION AND STATEMENT OF CONTRIBUTION

This chapter is valuable for a number of reasons. Firstly, it offers important insights into the identification and profiling of uncertainties. As noted by Patterson and Neailey (2002), while various authors discuss risk and uncertainty profiles in their work, very little has been written about their development and construction. In doing this, the chapter provides a range of uncertainties identified from primary data. Secondly, these uncertainties have been categorized by the application of a supply chain management framework, the uncertainty circle, to project uncertainties, which has not been undertaken previously. This is important, as it extends the notion of project uncertainty to include supply chain management, and refines a model that has previously been applied only in MTS sectors. The modelling of interactions between uncertainties is also an important and novel contribution to the overall method. Finally, the positioning matrix, which is classified according to the sources of supply chain uncertainty, provides a useful tool for analyzing the relative importance of uncertainty and observing the clusters from different sources of uncertainty.

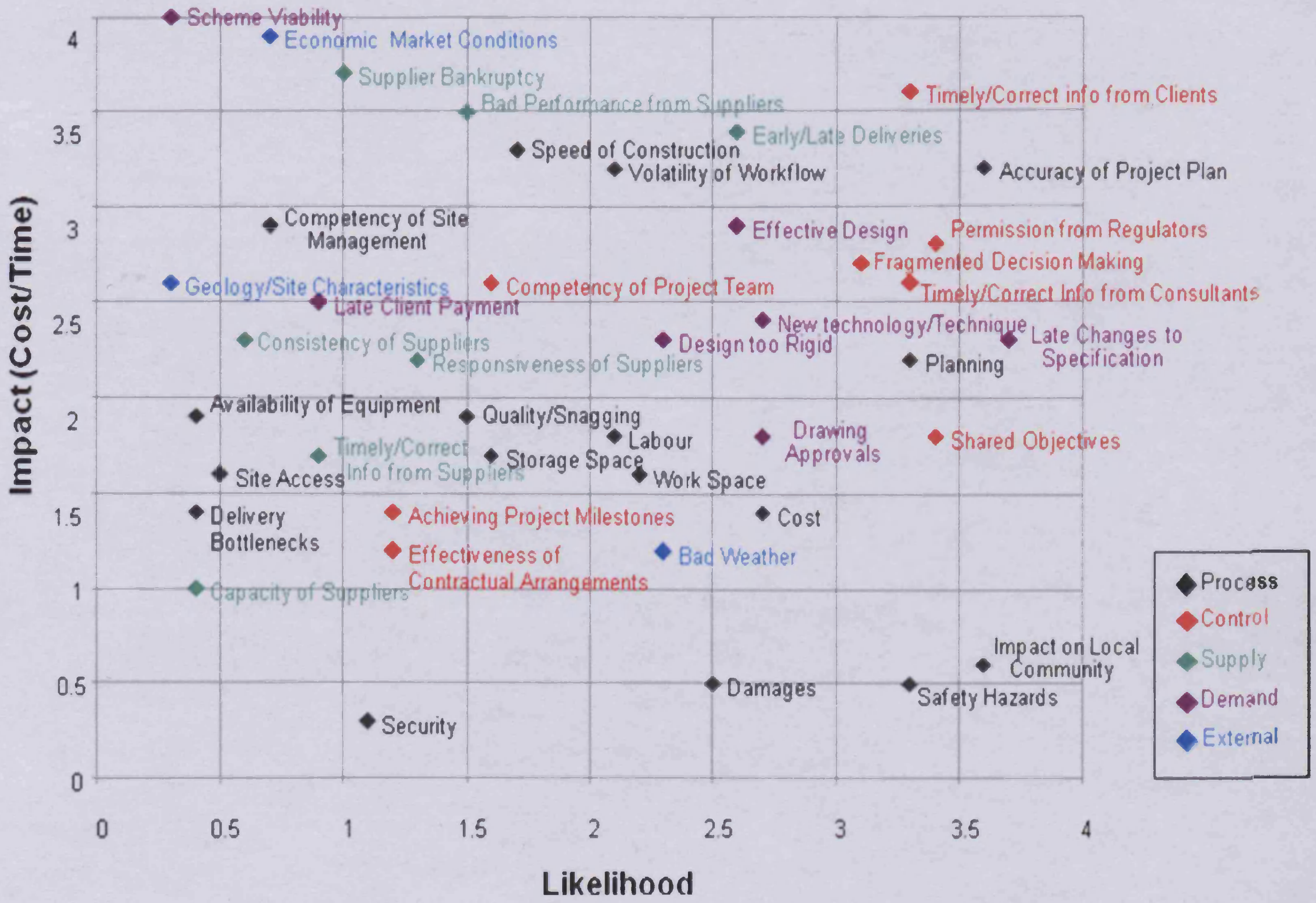


Figure 5.6: Positioning matrix to show relative importance of different uncertainties

The values and scores reported herein are based on primary data from 5 construction projects, covering residential and commercial sectors. Consequently, care must be taken in generalizing the uncertainties identified and scores to the wider construction industry. The values and scores reported may differ according to the nature of projects or the type of supply chain being analysed. The areas of the chapter that are mode widely applicable are those associated with the method of identifying and categorizing uncertainty. The key contribution of this chapter is, therefore, the development of a five-stage method for identifying and classifying uncertainty and its application to 5 construction projects. In doing this a number of important aims are achieved. The uncertainty circle is applied to the ETO construction sector and a model of interactions for the analysis of uncertainties is developed.

The importance and contribution of this chapter can be summarised as follows:

The supply chain uncertainty circle has not been applied in ETO Construction industries, and the interactions between the uncertainties have received little attention. A five-stage method of identifying, classifying uncertainty was developed, bringing together a range of tools and methods, which was applied to 5 construction projects. The method applies the uncertainty circle in project environments, and provides a model for modelling the interactions of uncertainty. This is the first time these techniques have been integrated into a holistic method to identify and categorize supply chain uncertainty, and then applied to a group of projects within the ETO construction sector.

5.7 CONCLUSION

In this chapter, the research question 'How can the sources of project uncertainty in engineer-to-order construction supply chains be identified and categorised?' was explicitly addressed. A five stage method was presented at the start of this chapter including the following steps: identify uncertainties, create uncertainty profiles, categorize uncertainties according to supply chain uncertainty source and originator, model interactions between uncertainties and use positioning matrix to identify severity. The empirical investigation reported in this chapter demonstrates how the framework may be applied to a group of projects. The method may be applied at the level of an individual project, or for selected groups of projects either within or between different companies.

For the first stage, individual project uncertainty profiles were developed for 5 different construction projects from 2 ETO systems. A generic list of project uncertainties was then developed from five projects in two systems. The findings show that there are forty two generic uncertainties in total, which can be categorised according to the sources of supply chain uncertainty as specified in the uncertainty circle model. The 42 uncertainties comprise 9 control uncertainties, 7 demand, 3 external, 16 process and 7 supply uncertainties.

A cause and effect diagram was developed to explore further the causes and relationships between different uncertainties. The causes of control uncertainties were found to be ineffective contractual arrangements, poor supply chain management and poor planning and project management. The root causes or process uncertainties were found to be inadequate resources, poor site logistics and poor site management. The causes of supply uncertainty were found to be supplier financial failure, inadequate supplier capabilities, poor visibility of site progress, orders not placed in time and late changes to orders. Finally, demand uncertainties were found to be caused by inadequate or inappropriate designs, delays approving designs, financial problems and market changes. The uncertainties were then plotted on a graph to show the likelihood of a negative impact occurring and the potential impact.

SUMMARY OF CHAPTER 5 AIMS

1) **Develop a method for the identification and categorization of uncertainty in ETO construction supply chains.**
   -A 5 stage method was proposed including:
2) **Apply the method to 5 construction projects**
   - Individual project uncertainties for 5 different projects have been summarised and presented
   - 42 generic uncertainties have been identified, which have been related to the different sources of uncertainty specified in the supply chain uncertainty circle
   - A cause and effect analysis for the uncertainties has been presented and discussed to show the connectivity and interaction between uncertainties
   - The uncertainties have been classified according to impact (time and cost) and likelihood dimensions to show the relative importance.

CHAPTER 6

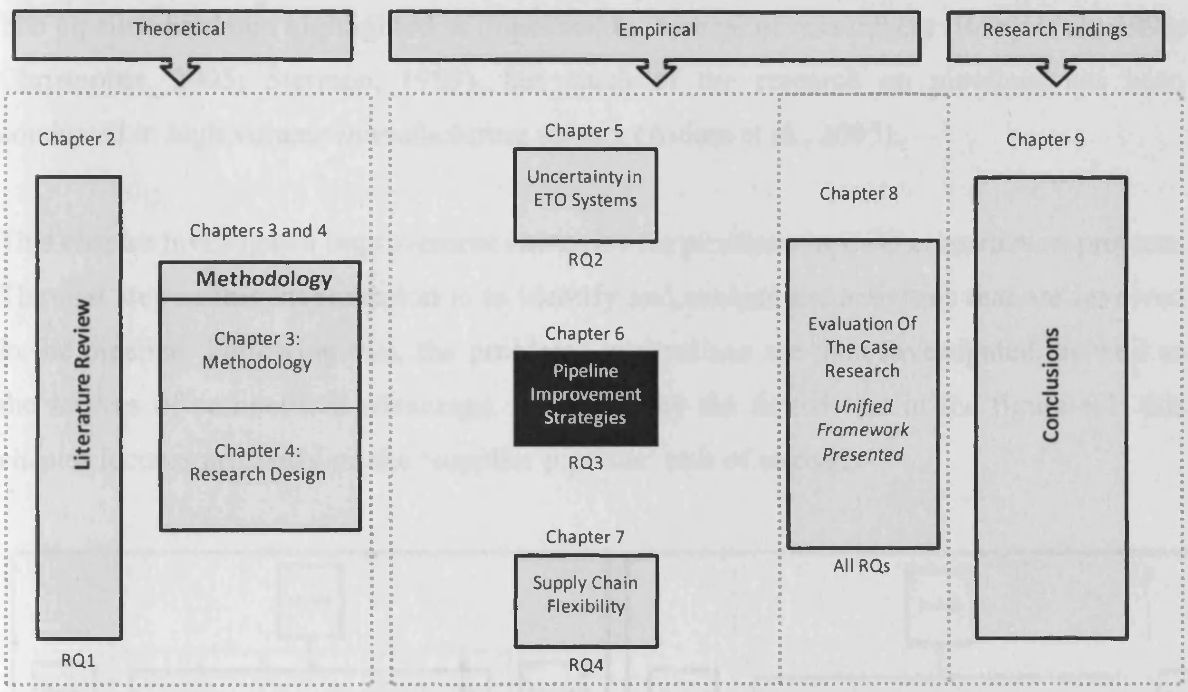
PIPELINE IMPROVEMENT STRATEGIES FOR ENGINEER-TO-ORDER CONSTRUCTION SUPPLY CHAINS

CHAPTER 6 AIMS

1. **Investigate pipeline activities in the range of supply chain structures feeding engineer-to-order supply chains**
2. **Analyse and compare lead times for different products**
3. **Identify and analyse problems in the pipeline**
4. **Identify and analyse sources of competitive advantage in pipelines**

RESEARCH QUESTION ADDRESSED

RQ3: How can organisations improve pipelines in ETO Construction supply chains?



6. INTRODUCTION

As noted in the literature review, a number of authors have suggested that the partnership literature for construction supply chains has placed too much emphasis on client relationships, as opposed to those that might arise upstream between contractors and their suppliers (Dainty et al., 2001a; Dainty et al., 2001b; Ireland, 2004; Proverbs and Holt, 2000). Despite this, the success of ETO projects relies heavily on the performance of manufacturers, suppliers, and subcontractors in the supply chain (Egan, 1998; Hartley et al., 1997; Hicks et al., 2000). A key challenge is to manage material deliveries from manufacturers in accordance with project requirements. This chapter considers 'pipelines' in the context of ETO supply chains, and addresses this gap relating to relationships between contractors and their suppliers. The pipeline has previously been described as the delay between an order being generated and the delivery of that order (Berry et al., 1998). The pipeline has been highlighted as important by a range of researchers (Berry et al., 1998; Christopher, 2005; Sterman, 1989), but much of the research on pipelines has been conducted in high volume manufacturing sectors (Aitken et al., 2005).

This chapter investigates improvement strategies for pipelines in ETO construction projects. The first step in this investigation is to identify and analyse the activities that are involved in the pipeline. Following this, the problems in pipelines are then investigated, as well as the sources of competitive advantage. As shown by the dotted line in the figure 6.1, this chapter focuses primarily on the 'supplier pipeline' unit of analysis.

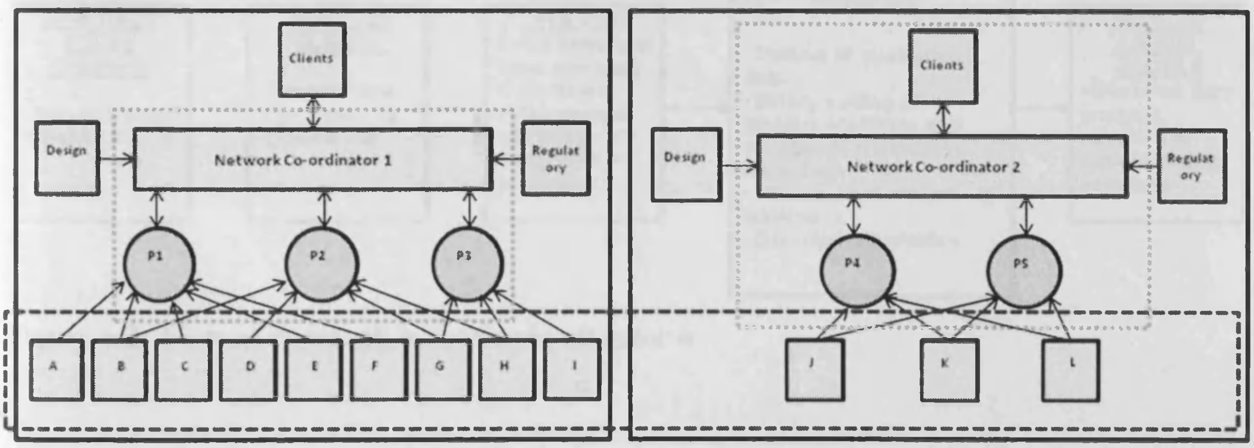


Figure 6.1: The two ETO systems and the primary focus of Chapter 6

6.1 METHOD OVERVIEW

This chapter presents the results of the 'pipeline survey', which is described in greater depth in the methodology chapter. The pipeline survey was conducted with 12 suppliers across the two systems, nine from system 1 and three from system 2. These suppliers were selected via snowball sampling (see figure 3.4), which includes and a range of criteria including supply chain structure and the relationship category with the network co-ordinator. Once a focal company from a pipeline was selected, the flow of research activities shown in figure 6.2 was undertaken.

The pipeline survey was designed to gather exploratory data about a supplier or subcontractor, which utilizes a mix of open and closed questions under different headings adapted from an approach used by Berry et al. (1998). The interview prompt list was arranged under different headings relating to company details, products and services, external environment (suppliers and customers), internal environment (focused on internal production issues) and strategic capabilities relating to flexibility. A further section investigates lead times, based on a template designed to probe areas of variability and uncertainty for the pipeline, and explores problems and sources of competitive advantage in the pipeline. The full pipeline survey is shown in appendix 4.

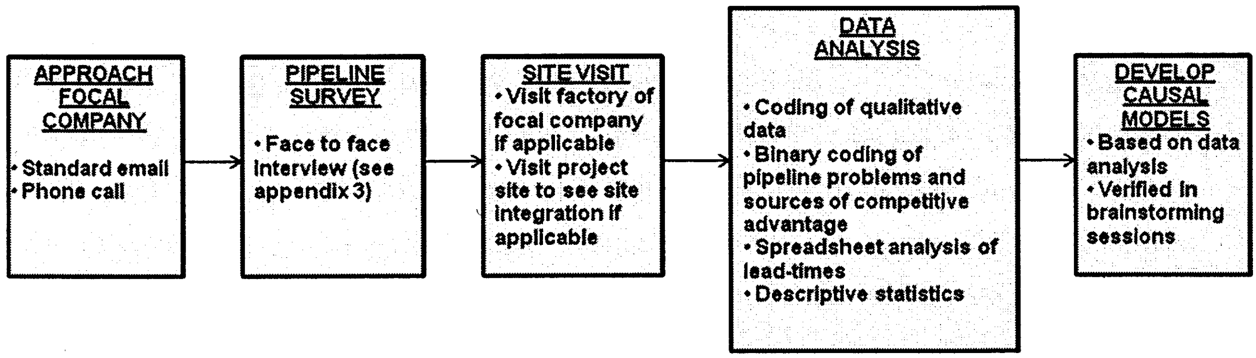


Figure 6.2: Flow of research activities in chapter 6

Three-point-time estimates for generic pipeline activities were established, along with the key problems experienced in the pipeline. Companies were asked to give a "most likely", an "optimistic" and a "pessimistic" lead time for the different activities. Companies also were asked to give a three-point estimate for the overall cycle-time that they quote to customers. Lead time information that was collected from each supplier was inserted into a spreadsheet for analysis. In some cases, these interviews were accompanied by factory visits and tours through the business functions. Lead time estimates were inserted into a spreadsheet to enable exploration by descriptive statistics. Bar charts and scatterplots are used to investigate various aspects of the lead time. The pipeline survey was analysed by coding responses from interviewees. Two areas are focused on the problems that are experienced in the pipeline and the sources of competitive advantage in the pipeline. A binary coding technique was used to code responses into theoretically meaningful categories. These themed responses were then consolidated on a spreadsheet. Input – output process maps were developed to support data collection and analysis.

The final step in the flow of research activities was to develop causal models for the problems that are experienced in the pipeline and the sources of competitive advantage in the pipeline. These were developed using the responses from the pipeline survey, and by brainstorming these models with industry contacts (for an overview of the brainstorming sessions see table 5.1).

6.2 OVERVIEW OF THE PIPELINE

The generic activities in the pipeline can be defined as: an initial enquiry, design and approval of a product, procurement of the relevant materials, manufacture and assembly, transport to the site and then final integration of the product with the site. Figure 6.3 shows these different activities as well as four potential stock holding points. The enquiry stage refers to the initial interest for an order made by a buying company. This stage will include exchange of all relevant information for pricing negotiations. The design stage, typically, includes negotiation of details of the drawings from architects and structural engineers. The approval stage refers to the final iteration whereby a final sign off from all parties is obtained. Clients, architects and main contractors will usually participate in the approval process.

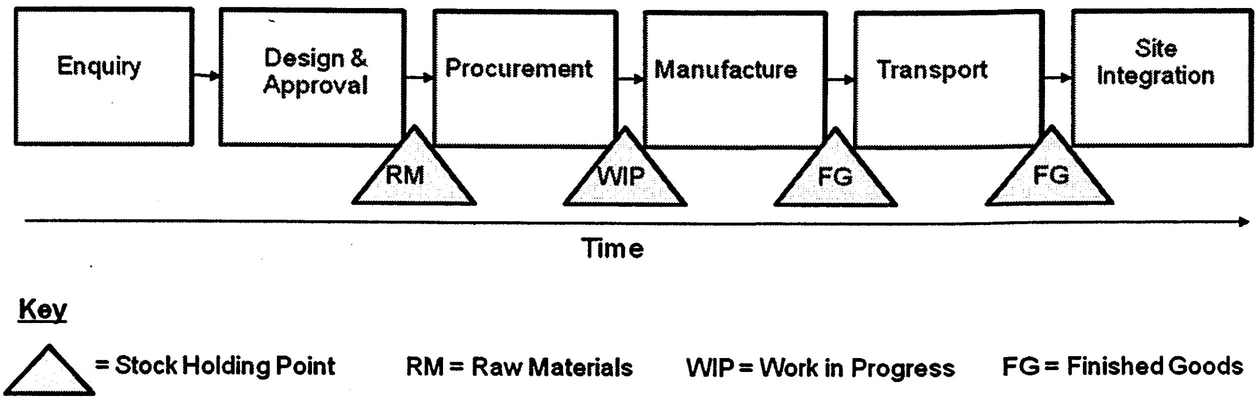


Figure 6.3: Generic pipeline activities and potential stockholding points

After the pricing and designs have been approved, a supplier will begin production planning. The companies in the pipeline differ in their approach to stockholding. Stock is held in different forms, with some holding generic stock of material inputs procured through ordering algorithms, others buy stock only after receiving an order. If a customer order is not satisfied through generic stock it will have to be procured through the supply chain after the customer order has been received. Alternatively, if a customer order is satisfied through generic stock it is likely that regular and consistent deliveries of materials will be procured irrespective of the timing of particular customer orders, as they are aggregated and smoothed to enable forecasting. Procurement lead times vary, depending on the complexity of the product and the extent of sourcing from overseas or by local suppliers.

Once the materials have been procured the manufacture can commence. Elevators and modular bathrooms have a relatively complex and deep product structure involving numerous sub-assemblies. Products such as roof trusses and timber have a relatively shallow product structure. After manufacture, finished goods may be held at either the supplier or at a 3rd party logistics provider. In the case of A, the lift manufacturer consolidated orders at a centre in mainland Europe and delivered elevators flat-pack to site. Many of the companies in this study held stock of finished goods only when changes to the due date made stockholding compulsory.

The next activity in the pipeline is to transport the finished goods, either straight after manufacture or from stocks of finished goods, to the site. Companies in the sample used either in-house transport or outsourced logistics service providers to transport their goods, sometimes combining both approaches. After delivery of a product, stock may be held on site until it is required for the project. Much of the metalwork produced in case E could be stored on site and, consequently, is often stored for up to 2 weeks before being integrated.

Alternatively, pre-cast concrete, supplied in case C, was delivered to site and, due to the size, transferred directly from the vehicle to the final location on the site and integrated immediately. Deliveries of pre cast concrete were delivered at set intervals to keep up with the workflow, allowing site labour to integrate each load into the site as it is delivered. Some companies used estimates for planning site installation. For example, in case B, the window supplier used 40 - 50 windows per week as a basis for installation planning. In one of the cases, the paint subcontractor often spent up to 9 months on site in larger projects providing support. A reminder of the details for the 12 supplier pipelines that are analysed and described in this chapter, and are shown in table 6.1. Whilst this table is already shown in the methodology chapter, it serves as a useful reminder for the reader.

Case	Sector	Employees	Turnover	Network Co-orindator	Projects	Primary Supply Chain Structure	Relationship with Network Co-ordinator
A	Elevators and Escalators	44000	£3.83bn	1	1	ATO	Strategic Partner
B	Windows	20-30	£4.5m	1	1 and 2	MTO	Preferred
C	Pre-cast Concrete	350	£230m	1	1	MTO	Preferred
D	Roof Trusses	150	£8m	1	2	MTO	Preferred
E	Metalwork	10,20	£1.25m	1	1	BTO	Approved
F	Brickwork	234	£15.7m	1	1	MTS	Approved
G	Timber Frame Systems	1400	£420m	1	2 and 3	MTO	Strategic Partner
H	Doors	205	£22.5m	1	3	BTO	Preferred
I	Builders Merchant	10600	£2bn	1	3	MTS	Approved
J	Paint	67	£11.5m	2	4 and 5	MTS	Strategic Partner
K	Modular Bathrooms	425	£53.8m	2	4 and 5	ATO	Strategic Partner
L	Drylining/Safety systems	52-100	£14m	2	4 and 5	BTO	Strategic Partner

Table 6.1: Summary of the supplier pipelines

5.3 ANALYSIS OF THE PIPELINE SURVEY

5.3.1 Supply Chain Structures

Using the attributes of different supply chain structures identified in the literature review chapter, table 6.2 shows the supply chain structure attributes of case pipelines. The pipeline survey included 3 BTO supply chains, 4 MTO supply chains, 2 ATO supply chains and 3 MTS supply chains. All these supply chains feed into one or more of the ETO project cases in the study. No cases of a primarily ETO or STS structure could be used. The different structures are now discussed in turn.

Buy-to-order supply chains

Case E, the metalwork subcontractor, Case H, the door manufacturer, and Case L, the drylining supplier, all had structures that closely resemble the BTO supply chain. In all these cases, no stock was held and raw materials were purchased in batches on a project to project basis when a customer order was placed. A small difference between the design strategies was evident. The customer could pick from wide range of standardised options for doors, whereas metalwork relied on designs from architects. Drylining was purchased in a standard format, which was then customised for size requirements. The door manufacturer held some of its most popular variants in stock, but the primary structure was BTO for delivery into major projects.

Make-to-order supply chains

In cases B (windows), C (pre-cast concrete), D (roof trusses) and G (timber frame systems) stocks of raw materials were held. This is typical of a make-to-order supply chain. For example, in case B, the window manufacturer held stock of timber and aluminium. The manufacturer of pre-cast concrete held generic stock of sand and aggregate for its pre-cast concrete, which was then mixed for specific orders. In the case of roof trusses, stocks of treated timber were held to complete its orders. The roof truss manufacturer differed slightly in its production methods as, alongside batch production of orders for projects, a job shop operated to complete one off orders with irregular size dimensions. Finally, the timber frame system manufacturer held stock of timber for incoming orders.

Assemble-to-order supply chains

Cases A (elevators) and K (modular bathrooms) held generic stock of 'modules'. In case A, the manufacturer held standardised modules locally and centrally for its European operations. However, some bespoke components were ordered on a project specific basis. In case K, modular platform modules of steel and wood, used as a basis for all units, were held in stock. This provided a standardized core that can be overlaid with customized design features for specific clients.

Case	Product	Primary Structure	Decoupling Point	Purchasing	Stock	Design	Production Method
A	Elevator	ATO	Assembly	Raw materials or buy pre assembled modules	Pre Assembled Modules	Pick from wide range of options	Project and Batch
B	Windows	MTO	Fabrication	Regular deliveries of raw materials	Raw Materials	Pick from wide range of options	Batch
C	Pre-cast Concrete	MTO	Fabrication	Regular deliveries of raw materials	Raw Materials	Standard concrete mix – customised size/dimensions	Batch
D	Roof Trusses	MTO	Fabrication	Regular deliveries of raw materials	Raw Materials	Standard timber finish – customised size and arrangement	Batch and Job
E	Metalwork	BTO	Purchasing	Schedule when order received	No Stock	Take design as given by architect	Batch
F	Brickwork	MTS	Central Distribution	Regular deliveries of raw materials	Finished goods held centrally	Standard designs	Batch/Flow
G	Timber Frame Systems	MTO	Fabrication	Regular deliveries of raw materials	Raw Materials	Pick from wide range of options	Batch
H	Doors	BTO	Purchasing	Schedule when order received	No stock	Pick from wide range of options	Batch
I	Timber	MTS	Central Distribution	Regular deliveries of raw materials	Finished goods held centrally	Standard designs – range of finishes	Batch/Flow
J	Paint	MTS	Central Distribution	Regular deliveries of raw materials	Finished goods held centrally	Standard designs – range of finishes	Batch/Flow
K	Modular Bathrooms	ATO	Assembly	Regular deliveries of raw materials	Pre Assembled Modules	Pick from wide range of options	Project and Batch
L	Drylining /Safety Systems	BTO	Purchasing	Schedule when order received	No stock	Standard timber finish – customised size and arrangement	Batch

Table 6.2: Supply chain structures of cases in the pipeline survey

Make-to-stock supply chains

Cases F (brick and block), I (timber) and J (paint) all held stock of finished goods to meet customer demand. After manufacture, stock is held and then distributed to a site on a project by project basis, so the last activity, the distribution, is customised. These cases are typical of a MTS supply chain. For example, in case F, standardized bricks and blocks were produced in high volume and customers ordered bulk amounts of bricks and blocks and then 'called off' their requirements from working stock as projects progressed.

6.3.2 Scope of Responsibility

For the companies investigated in this study, there is considerable diversity regarding the extent of responsibility that each company undertook for different activities in the pipeline. Table 6.3 summarises the scope of responsibility taken on by each of the case companies in the pipeline survey. The table indicates the potential in-house capabilities by the companies. It shows that rarely can a single organisation provide all the capabilities required to complete all pipeline activities. A range of organisations, material suppliers, 3rd part logistics suppliers, specialist design consultants and equipment suppliers, often have to work together to complete all activities in the pipeline. The companies in cases A (elevators) and K (modular bathrooms) were the only ones who were able to offer a complete work package to customers without outsourcing certain activities. In case F, the company acts as a co-ordinator for brickwork packages and has direct control over very few aspects of the pipeline. It specialises in managing the different contractors involved. It is worth noting that both network co-ordinators referred to companies that can offer comprehensive work packages as subcontractors and those that purely offer material supply as suppliers.

The amount of design work required varies across the different product groups. Table 6.3 indicates where companies have the capability to work with customers and contribute to the design of areas within the project. Only the focal companies in cases E (metalwork), F (brick and block) and I (timber) did not have the capability to support customers in design aspects for the project. In case A, the manufacture of elevators had the capability to support clients on large complex projects with large amounts of design work. Five percent of its business consisted of large ETO projects. For the manufacture of roof trusses, existing designs were reused for different projects, where dimensions and layout were normally very different. The focal company in case E, on the other hand, supplied metalwork packages to contractors and assumed responsibility for all activities in the pipeline other than design. The company did not have the necessary accreditations to take responsibility for design work.

Case	Design	Assembly	Transport	Site Integration	Equipment	Labour
A	✓	✓	✓	✓	✓	✓
B	✓	✓		✓	✓	✓
C	✓	✓		✓	✓	✓
D	✓	✓	✓			
E		✓	✓			
F						
G	✓	✓	✓	✓	✓	✓
H	✓	✓				
I			✓			
J	✓		✓	✓	✓	✓
K	✓	✓	✓	✓	✓	✓
L	✓		✓	✓	✓	✓

Table 6.3: Scope of responsibility of focal companies in each of the pipelines

Transport and logistics capabilities are a further activity in the pipeline where the scope of responsibility changes in different pipelines. In cases B, C, F and H the focal company did not have in-house transport capabilities, relying on the services of a 3rd party logistics provider. For example, the focal company in case B was a UK branch of a Scandinavian window manufacturer who is integrated vertically with the timber-sourcing operations. All logistics operations were managed by a 3rd party logistics provider, who was responsible for material handling, stockholding and transport. In case C, the pre-cast concrete manufacturer assumed responsibility for all activities in the pipeline other than the transport, which was also managed by a 3rd party logistics company.

Another area of the pipeline where focal companies differ is their approach to site integration, which in many cases requires plant and labour for installation of a product. The focal companies in cases D, E, F, H and I did not offer site integration services. They operated on a 'supply only' model. The focal company on case A, the lift manufacturer, planned for 4-6 weeks on-site for installation, including 1 week to install, 1 week to test, 2 weeks to make good, 1 week final testing. Finally there a 12 month service period was offered. It supplied all the materials, labour and equipment required to install the elevator on site. Alternatively, in case D, the roof truss manufacturer was responsible for all activities in the pipeline other than installation. The company has had problems in the past finding enough local labour to install its products on the various projects it is working on. It took the decision to cease offering an installation service. In case L, the supplier of drylining and safety system, the focal company made to order, while its drylining suppliers made-to-stock. It combined labour, safety systems equipment and additional metalwork, to offer a safety system 'package' to customers, which is all installed on site as part of the package.

6.3.3 Lead-times

Overall Lead-times

Overall order to delivery cycle-times were obtained as part of the pipeline survey, along with an estimate of optimistic and pessimistic lead-times. This represents a 3-point estimate that the focal companies would offer to customers. This quoted order cycle time included all activities other than site integration and was quoted in weeks. Figure 6.4 shows the quoted order cycle time plotted against the variability of this order cycle time. The variability refers to the difference between optimistic and pessimistic lead-times. A trend that emerges from the figure is that the higher the lead time, the greater the degree of variability that exists. This concurs with Berry et al. (1998) in their pipeline survey of companies in the UK. This investigation of overall cycle-time and variability precedes a more details analysis of lead-times for pipeline activities. This is addressed in the rest of this section.

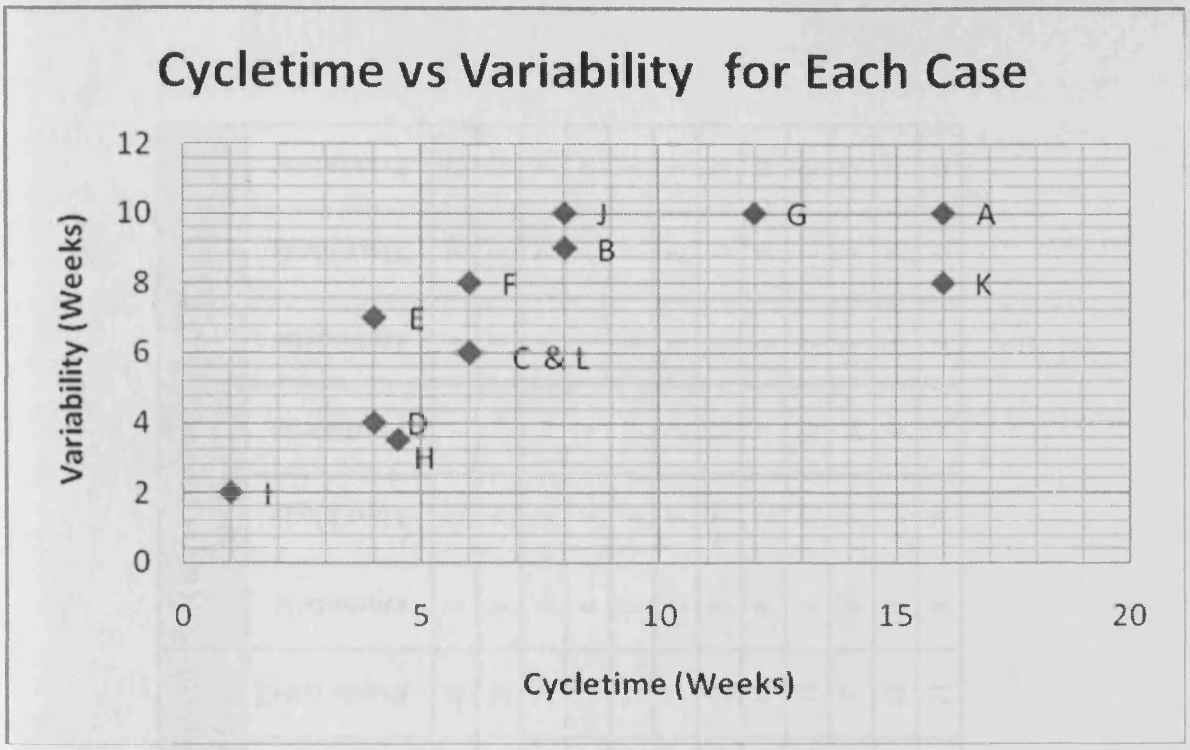


Figure 6.4: Order-cycle-time plotted against variability of order-cycle-time

Detailed investigation of lead-times

A master table of lead-times for all activities in the pipeline across all the cases is shown in table 6.4. The optimistic, most likely and pessimistic lead-times for all pipeline activities are displayed. The unit of measurement shown in the table is days. The enquiry, design and approval activities have been grouped together. The lead-times for the site integration phase are not shown as, in some of the cases, the focal companies in the pipeline study do not take responsibility for site installation. Therefore, they were unable to offer accurate lead-times for this activity.

Case	Enquiry, design and approval			Procurement			Stock			Manufacturing and Assembly			Stock of finished goods			Transport		
	Optimistic	Most likely	Pessimistic	Optimistic	Most likely	Pessimistic	Optimistic	Most likely	Pessimistic	Optimistic	Most likely	Pessimistic	Optimistic	Most likely	Pessimistic	Optimistic	Most likely	Pessimistic
A	14	28	56	14	21	28	0	14	56	14	28	42	0	7	14	4	7	12
B	28	42	112	7	14	21	1	4	7	14	21	28	0	0	14	4	7	12
C	28	35	56	0	1	2	1	2	7	14	19	21	0	1	14	1	1	2
D	7	14	21	1	1	2	1	7	14	1	1	7	0	2	4	1	1	2
E	28	26	49	0	1	2	0	2	7	14	19	21	0	3	14	0	1	2
F	7	14	56	1	2	112	0	0	0	1	2	3	0	1	7	1	2	5
G	28	35	126	1	7	56	2	4	7	1	7	14	0	7	14	1	1	2
H	14	21	42	1	7	21	0	2	7	1	7	14	0	2	7	2	7	14
I	0	2	49	1	2	7	2	4	7	2	3	14	2	4	21	1	1	2
J	7	28	364	1	7	21	0	14	21	0	3	7	0	7	56	1	1	2
K	70	84	126	42	49	70	0	2	4	7	14	28	0	1	1	1	1	3
L	14	21	28	2	3	7	0	0	0	7	14	21	0	7	14	1	1	2

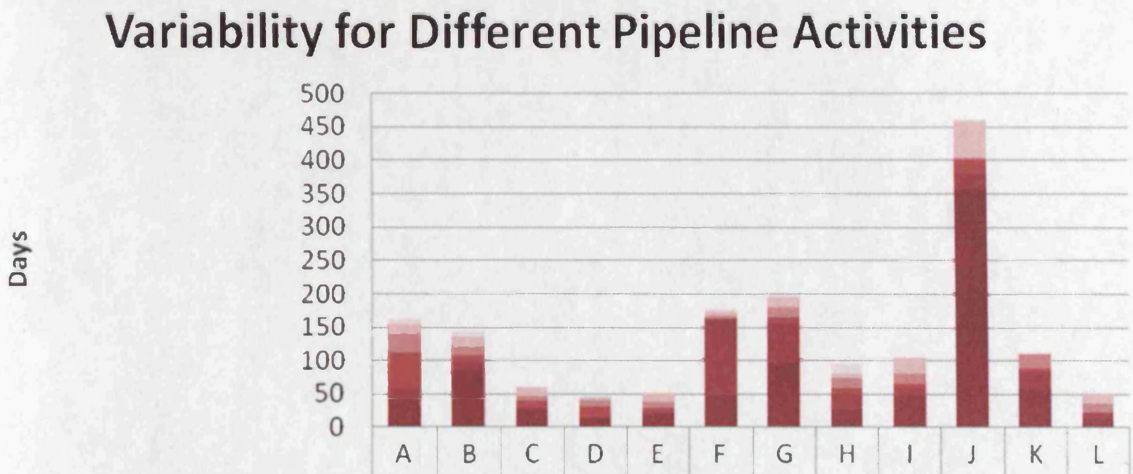
Table 6.4: Lead times for pipeline activities

Figure 6.5 shows the most likely lead-times for pipeline activities in the different cases. Modular bathrooms (K) and elevators (A) had the longest pipeline lead times with 151 and 105 days respectively. Timber (I) and brick and block (F) had the shortest pipeline lead-times with 16 and 21 days respectively. If the most likely lead-times are summed and averaged, it is possible to see that the enquiry, design and approval stage accounts for the largest proportion of lead-times. The average lead-time for this stage was 29 days, which accounts for 56% of the average pipeline lead-time. Procurement accounted for 18%, manufacturing 21% and transport 5%. Stockholding was relatively low, with an average of 4.7 days for raw materials or strategic stock and 2.9 days of finished goods.

	A	B	C	D	E	F	G	H	I	J	K	L
Transport	7	7	1	1	1	2	1	7	1	1	1	1
Stock of Finished Goods	7	0	1	2	3	1	7	2	4	7	1	7
Manufacture & Assembly	28	21	19	1	19	2	7	7	3	3	14	14
Strategic Stock	14	4	2	7	2	0	4	3	4	14	2	0
Procurement	21	14	1	1	1	2	7	7	2	7	49	2
Enquiry, Design & Approval	28	42	35	14	26	14	35	21	2	28	84	21

Figure 6.5: Most likely lead times for individual pipelines

The range between optimistic and pessimistic lead-time estimations was used to calculate the lead-time variability. Figure 6.6 shows there was most cumulative variability in the paint pipeline, case J. In particular, the enquiry, design and approval stage in the paint pipeline was very variable, ranging from 7 days to a year. The focal company in the paint pipeline works on very large projects and delivers complex and comprehensive packages, so it is usually communicating with site management about design details for the majority of the planning and construction phase of a project. There was least cumulative variability in the roof truss pipeline, 45 days, followed by timber, at 51 days.



	A	B	C	D	E	F	G	H	I	J	K	L
Transport	8	8	1	1	2	4	1	15	1	1	2	1
Stock of Finished Goods	14	14	14	4	14	7	14	7	22	56	1	14
Manufacture & Assembly	28	14	7	9	7	3	16	16	15	3	21	14
Strategic Stock	56	9	9	16	7	0	8	7	8	21	4	0
Procurement	14	14	2	1	2	114	58	23	9	23	28	8
Enquiry, Design & Approval	42	84	28	14	21	49	98	28	49	357	56	14

Figure 6.6: Cumulative variability for individual pipelines

To give an indication of the average variability found in different pipeline activities a box plot diagram has been developed, which is shown in figure 6.7. This shows the variability of specific pipelines activities when the case values are averaged. The spread of the boxplot whiskers show the variability of the different pipeline activities. All pipeline activities other than manufacturing and assembly have a positive skew. The pessimistic lead-times are generally much further away from most likely lead-times than optimistic lead-times. The figure also shows that the enquiry, design and approval stage is the most variable pipeline activity, with an average variability of 70 days. The average optimistic lead-time for enquiry, design and approval was 20 days, the most likely lead-time was 29 days, and the pessimistic lead-time was 90 days. Transport is the activity with the shortest most likely lead-time, having an average most likely time of just over 2.5 days. Transport is also the least variable, with the difference between average optimistic and pessimistic lead-times being 4.5 days.

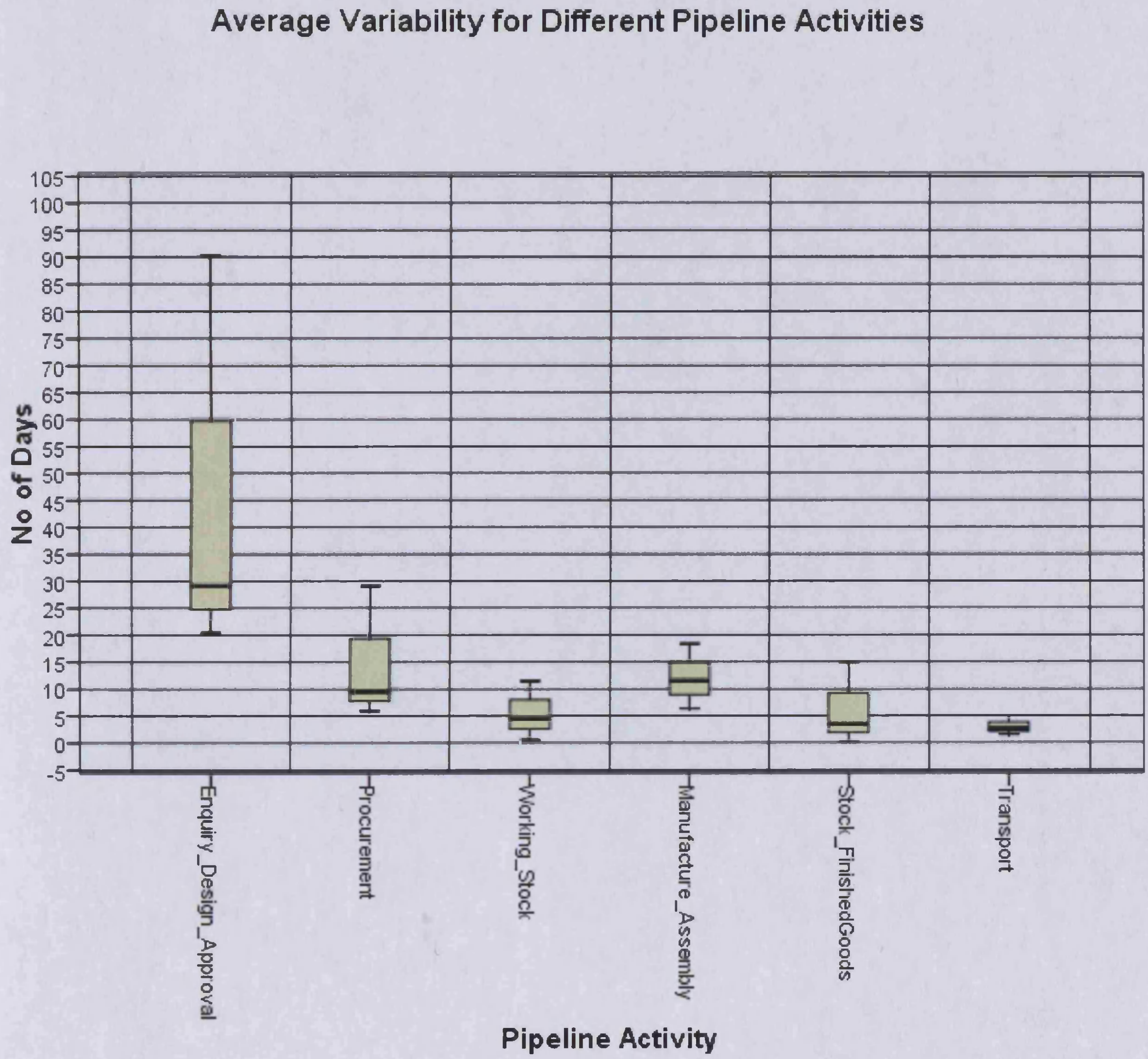


Figure 6.7: Average variability and average lead times for different pipeline activities

6.4 PROBLEMS IN THE PIPELINE

The pipeline survey also collected data relating to the problems experienced in the pipeline. Table 6.5 shows a summary of the different problems experienced in each of the pipelines. Ten generic problems have been identified (shown across the top of the table). They have been sorted, horizontally, by the most frequently cited problems and, vertically, by the pipeline that cited the most problems. A causal modelling diagram has been developed in order to highlight the cause of problems and their solutions. This is shown in figure 6.8. The generic problems along with their causes and potential solutions are now discussed in turn.

	Problems in the Pipeline*										
Case□	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	**Total**
A	0	1	1	0	0	1	0	0	1	1	5
D	1	1	1	0	1	0	0	1	0	0	5
K	1	0	1	0	0	1	1	0	0	0	4
C	0	1	0	1	0	0	1	0	0	0	3
G	1	0	0	1	0	1	0	0	0	0	3
B	0	1	0	1	0	0	0	0	0	0	2
F	0	1	0	0	0	0	0	1	0	0	2
H	1	0	0	0	1	0	0	0	0	0	2
I	1	0	0	0	0	0	0	0	1	0	2
L	0	0	1	0	1	0	0	0	0	0	2
E	1	0	0	0	0	0	0	0	0	1	2
J	0	0	0	1	0	0	0	0	0	0	1
Total	6	5	4	4	3	3	2	2	2	2	

**1* = Design Changes/Incorrect Specification, *2* = Establishing Site Readiness *3* = Labour, *4* = Information Exchange, *5* = Supply Risks, *6* = Integrating With Other Trades, *7* = Access Issues, *8* = Excessive Product Variation, *9* = Payment & Chains of Custody, *10* = Tender Uncertainty

□A = Elevators, B = Windows, C = Pre cast concrete, D = Roof Trusses, E = Metalwork, F = Brick and Block, G = Timber frame systems, H= Doors, I = Timber, J = Paint, K = Modular bathrooms, L = Drylining.

Table 6.5: Binary coding of problems in the pipeline

Problem 1 - Design Changes/Incorrect Specification

As has already been noted, the design and approval process represents a major time bottleneck and proved to be the most variable of all pipeline activities analysed. This is cited as a problem in cases D, E, H, G, I and K. In the design of modular bathrooms, getting the design right early on saves a lot of time and effort later on. Design changes that are made late in the pipeline can be particularly costly. The manufacturer in this case had made significant investments in design software and expertise. Design changes were also a problem for the timber frame manufacturer. Initial designs were not usually prepared for a timber frame construction method, so they had to be converted. Late design changes were so costly that the company insisted on a design freeze cut off point. Cases H and I, doors and timber, both cited incorrect specification from designers as a significant problem in the pipeline. Design changes and incorrect specifications can be the result of a combination of late changes made by the client, initial designs that are too vague, and suppliers receiving designs too late in the project to make any realistic contributions or react to any problems. Solutions include having a design freeze and keeping quotes open and subject to variation.

Problem 2 – Unable to establish site readiness

Establishing site readiness for delivery is also frequently identified as a problem. Cases A, B, C, D and F all register this problem. The due dates are agreed upon early in the tender process. Deliveries and installation require careful coordination of trades and activities to meet this due date, and when the supplier is ready to deliver the initial due date agreed is either too early or too late. If the supplier has poor visibility of site progress, or if the communication between the site management and supplier are poor, changes to the due date will not be registered. A symptom of not being able to establish site readiness is the requirement to store finished goods. This often incurs a financial cost to the supply chain and difficulties managing labour for installation. In the case of the lift manufacturer delivery dates given in the planning stages are nearly always too early. One of the interviewees estimated that 9 times out of 10 the site is only half way through the preceding activity when the product is ready to be delivered. Pre-cast concrete, due to its bulk and weight, once cut and set, needed to get to the site and be put in place quickly. This makes establishing site readiness for delivery a premium.

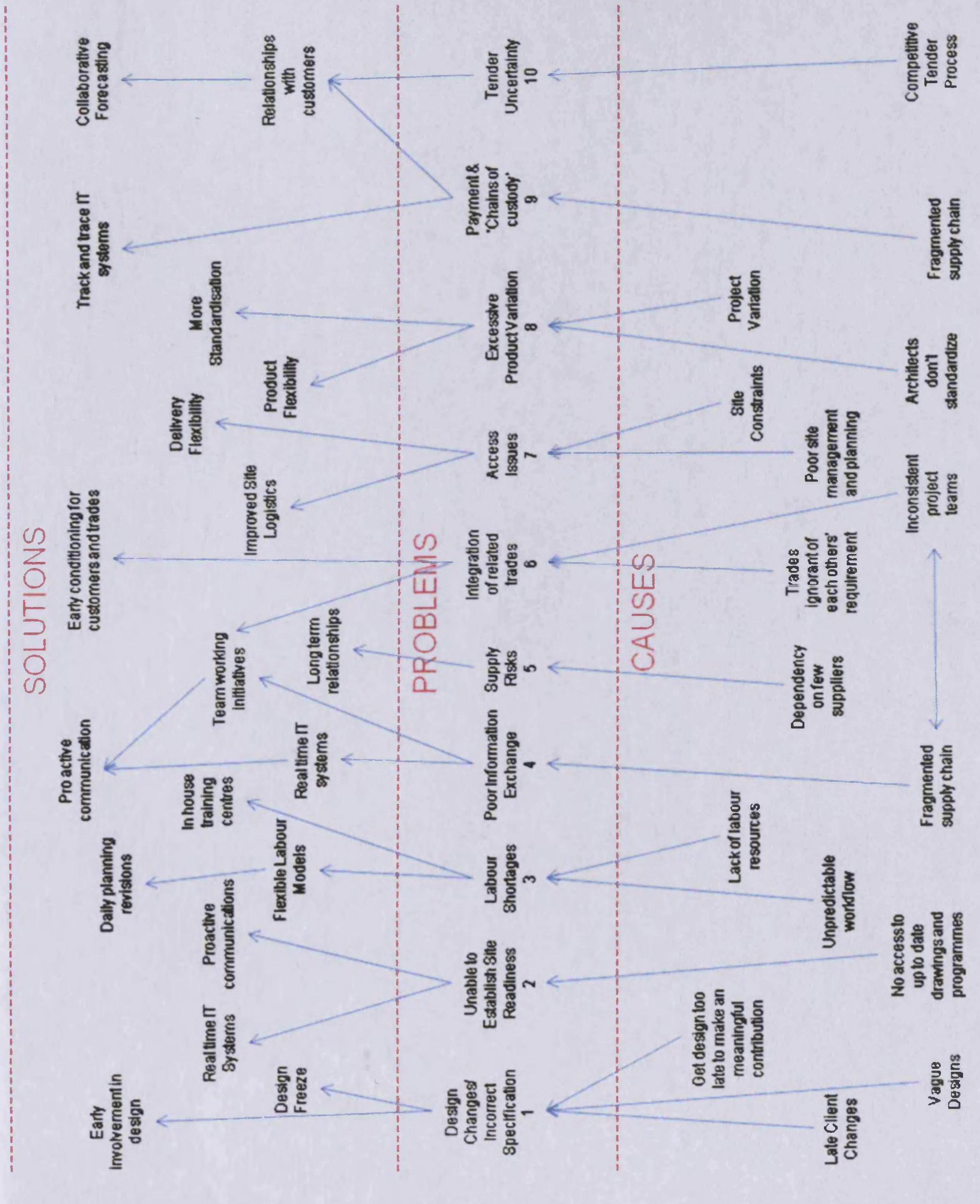


Figure 6.8: Causal modelling for problems in the pipeline

A cause of this poor visibility is a lack of access to updated drawings and programmes. Solutions include information technology (IT) systems that facilitate visibility of project progress and good proactive communication between supply chain members. Another solution to this problem is the use of consolidation centres or a strategic stockholding points so that stock can be held and deliveries controlled to ensure that the site is ready to accept.

Problem 3 – Labour Shortages

Labour is the third most frequently cited problem. Cases A, D, K and L all refer to this as a problem. For elevators, labour at peak times could be 'difficult to juggle', especially for site installations. The roof truss manufacturer found it difficult to recruit drivers for its in-house fleet and in finding local labour for the factory. The company had to stop offering installation services as adequate labour 'gangs' could not be recruited effectively. The manufacturer of modular bathrooms finds it difficult to get skilled joiners and fitters and has initiated its own in house training facility to overcome this problem. The drylining subcontractor found labour a 'major constraint for completing tasks'. The causes of this were unpredictable workflow and the lack of labour resources. Possible solutions include in-house training schemes to develop local labour and flexible labour models through combinations of in-house and outsourced labour.

Problem 4 - Information Exchange

Getting the correct information at the right time was perceived as a significant problem for pipeline activities. This was identified as a major problem in cases B, C, G and J. In the case of the window suppliers, getting appropriate and up to date information from clients, consultants and main contractors was seen as the most significant problem in the pipeline, especially the acquisition of up-to-date drawings and sizes. For the pre-cast concrete manufacturer, a lack of information about hole penetration points for casts and fittings, as well as vague designs and enquiry information, was a difficulty. The original design information received by the timber frame system manufacturer was not usually tailored for timber frame designs, so technical staff were employed to convert drawings and information to the correct format. Furthermore, design information was usually received too late to make meaningful improvements.

The paint subcontractor in the Pipeline J required 3 types of information to complete a project: programme details which include a start date, a schedule of works and a finishing specification. Typically, at least 1 of these pieces of information was not received early enough. The main cause of this was a fragmented supply chain. For each project that suppliers work on, they are often working as a part of different project coalitions as opposed to a consistent, established supply chain. It is difficult to instil a sense of team working into such as supply chain and real time information exchange is often lacking. Possible solutions here include proactive and flexible communication systems, early involvement in design for suppliers and meetings, facilitated by the network co-ordinator, to foster relationships between different groups of suppliers that must work together.

Problem 5 - Supply Risks

After integrating with other trades and establishing site readiness, supply risks were the next mostly frequently cited in the pipeline survey. Cases D, H and L all alluded to supply risks. The door manufacturer suffered from problems in global supply networks, as there were only a few specialist suppliers of specialist parts. Case L, the dry-lining supplier, was dominated by terms and conditions of the three big suppliers of dry-lining timber. Finally, the roof truss manufacturer was at risk from the lack of suppliers of the plating which binds rook truss beams. This was integrated with design software of which there are only a few specialist suppliers in the UK. The cause is attributed to dependency on a few suppliers, which reinforces the need for long term partnerships if there are no alternative sources of supply.

Problem 6 - Integration with other trades

Cases A, K and G all cited integrating with other trades as a problem. This comes at the end of the pipeline in the site integration phase. This is connected with the problem of establishing site progress, as frequently the activities of other trades are not completed on time and this delay is not communicated effectively. For the timber frame manufacturer problems arose when the groundwork was insufficiently prepared. The elevator manufacturer has to interface with many trades, and this causes problems with fragmentation of the supply chain, inconsistent project teams and trades being ignorant of each others' requirements. Potential solutions include educating trades and team working initiatives to encourage discussion between related trades. Work package teams have been suggested.

Problem 7 - Access Issues

The inability of the suppliers to access sites is highlighted by two of the case pipelines. Cases C and K both regularly experienced difficulties when planning access points for sites. One of the key challenges for the manufacturer of modular bathrooms is ensuring clear access and an uninterrupted work area on site. The manufacture of pre-cast concrete also experienced problems with site access. Typically, for the delivery of pre-cast concrete, large volumes and frequent deliveries were made on to site. Space is required for lifting equipment and a large work area is required.

Access issues can be caused by poor site management and planning. If site work areas and access points are not managed to ensure materials can flow to required areas then access will become an issue for suppliers. Some sites, however, may be severely constrained in terms of access points, especially if they are situated in dense urban areas. The solutions to this problem lie with the site management. Suppliers and site management may work together to promote delivery flexibility. This may also involve improving site processes. Network co-ordinator 2 has developed a specific area within the business that advises different site management teams on site logistics, access and on site material flows.

Problem 8 – Excessive Product Variation

A further problem in the pipeline is excessive product variation caused by architects' designs. Companies D and F perceived this as a problem. For the manufacture of roof trusses, architects frequently liked to introduce new designs. A key challenge for the brick and block supply chain was to get architects and engineers to select a package of bricks from an established list to suit aesthetic and strength requirements, as it is very costly to introduce new designs. The root cause of this problem is that suppliers deliver to projects that vary in scope, scale and design requirements. Architects do not have incentives to standardize elements of their designs, and product variation proliferates as a result. Two potential solutions are increased product flexibility capabilities at the supplier level or more standardisation from architects, with due care and attention to design for manufacture.

Problem 9 - Payment and 'chains of custody'

Payment and establishing chains of custody was also highlighted as a problem. Chain of custody refers to the auditing and tracing of changing ownership of materials as they flow through the supply chain and the corresponding payment and quality assurances for these materials. Companies A and I both highlighted this as a problem. In the case of the lift manufacturer customer payment was perceived to be an important issue. The organisational processes were system driven, so, in some cases, employees were unable to proceed with orders until the system requirements have been fulfilled. In many cases late payments from customers held up these processes and have delayed delivery. Company I, the timber supplier, stated that commercial negotiations and payment have, in the past, held up deliveries. A cause of this is a fragmented supply chain. A possible solution is integrated, supply chain track and trace systems and good customer relationships.

Problem 10 - Tender uncertainty

A further problem was the competitive tendering process. This supports other studies that suggest that competitive bidding in project procurement is a key contributor to overall lead time (Elfving et al., 2005). Companies A and E both stated that the tender process was a problem. A network co-ordinator, typically, will send an enquiry out to a number of potential subcontractors for work packages and material supplies, selecting each project through a competitive tendering mechanism. More consistency from clients and contractors in purchasing arrangements with effective framework or collaborative agreements would help suppliers and subcontractors forecast and build relationships for improved service. This type of relationship building could result in collaborative forecasting for prospective orders.

6.5 SOURCES OF COMPETITIVE ADVANTAGE IN PIPELINES

Competitive advantage is the search for a favourable position in an industry (Porter, 1985). The resource based view of the firm argues that companies that are able to sustain competitive advantage from the resources and capabilities that they accumulate (Grant, 1991; Peteraf, 1993). Dyer and Singh (1998) extended this view of the firm of the unit of analysis when they observed that a pair or network of companies can develop relationships that result in sustained competitive advantage. In the field of supply chain management, studies have highlighted that supply chain management practices can have a direct impact on competitive advantage (Christopher, 2005; Li et al., 2006; Towill, 1997a). According to Christopher (2005), competitive advantage can be found in the ability of the organisation to differentiate itself, in the eyes of the customer, from its competition and by operating at a lower cost and hence at greater profit. Successful companies either have a cost advantage or they have a value advantage, or a combination of the two. This section addresses the sources of competitive advantage that can be developed in supplier pipelines for project environments.

Table 6.6 shows a summary of the sources of competitive advantage in the different pipelines. Ten sources have been identified (shown across the top of the table). They have been sorted, horizontally, by the most frequently cited sources and, vertically, by the pipelines that cited the most, and least, different sources. As with the previous section, a causal modelling diagram has been developed in order to show relationships between sources, enablers and benefits. This is shown in figure 6.9. Each source of advantage is now discussed in turn.

Source 1 - Specialist Expertise

The most widely cited source of competitive advantage, along with supply chain integration, is specialist expertise. Cases G, C, D, H, E and J all cited this as a source of competitive advantage. It refers to mastery of a particular product, service or combination of goods and services. In particular, they referred to the ability to offer support for clients in tendering for projects and for providing advice specifically relating to their expertise. The timber frame system and roof truss manufacturer both referred to the importance of design expertise when dealing with customers. The manufacturer of pre-cast concrete highlighted the ability to advise clients on strength requirements, hole penetration points, timings and resource requirements as a major contributor to winning orders. The paint subcontractor perceived that the ability to advise clients effectively on a 'package' of requirements is crucial in securing repeat business. This package would include recommendations on labour requirements, time implications and finishing specification.

	Sources of Competitive Advantage*										
Case□	***1***	***2***	***3***	***4***	***5***	***6***	***9***	***7***	***8***	***10***	**Total**
A	0	1	1	0	0	1	1	0	1	0	5
J	1	0	0	0	1	1	1	0	0	1	5
G	1	1	1	0	0	0	0	1	0	0	4
K	0	1	1	0	1	0	0	0	1	0	4
D	1	1	0	1	0	0	0	0	0	0	3
B	0	0	0	1	0	1	0	1	0	0	3
C	1	0	0	0	0	0	1	0	0	0	2
H	1	0	0	0	0	0	0	0	0	1	2
I	0	1	0	1	0	0	0	0	0	0	2
E	1	0	0	0	0	0	0	0	0	0	1
F	0	1	0	0	0	0	0	0	0	0	1
L	0	0	0	0	1	0	0	0	0	0	1
	6	6	3	3	3	3	3	2	2	2	

**1* = Specialist Expertise, *2* = Supply Chain Integration, *3* = Information Technology Systems, *4* = Logistics , *5* = Labour, *6* = Management Systems and Processes, *7* = New Product and Process Innovation, 8 = Manufacturing Excellence, *9* = Modularity, *10* = Flexible Organisational Structure

□A = Elevators, B = Windows, C = Pre cast concrete, D = Roof Trusses, E = Metalwork, F = Brick and Block, G = Timber frame systems, H= Doors, I = Timber, J = Paint, K = Modular bathrooms, L = Drylining.

Table 6.6: Binary coding of sources of competitive advantage

The enablers for specialist expertise were highlighted as highly trained staff and investment in training facilities. In case K, an in-house training school had recently been set up to maintain a pool of skilled labour. The timber frame system manufacturer also had a skills academy. Expertise supports the capabilities to advise clients, contribute to designs and can enable a suitable and well positioned mix of products for its customers.

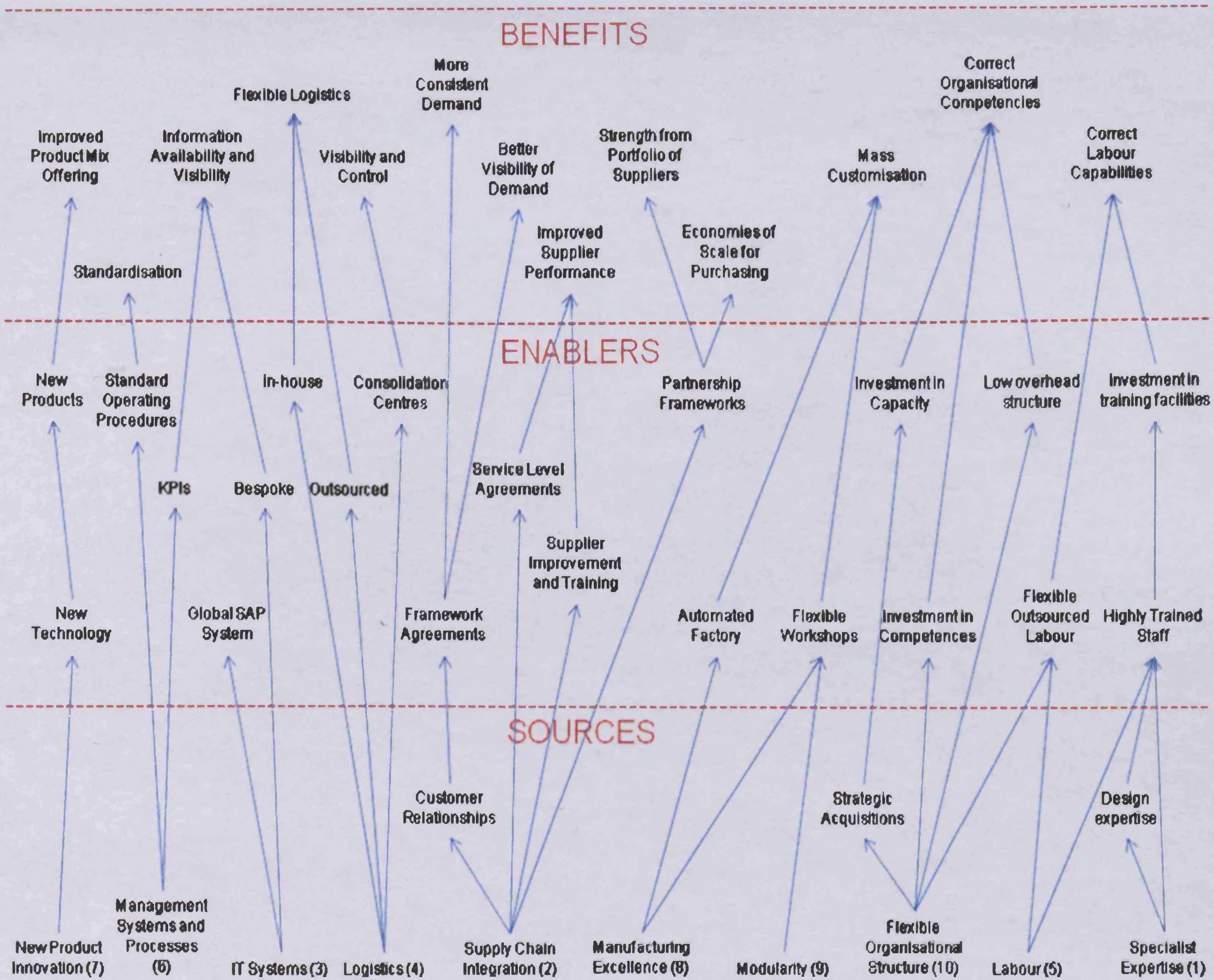


Figure 6.9: Causal modelling for sources of competitive advantage

Source 2 - Supply Chain Integration

Supply chain integration was, jointly with specialist expertise, the most widely perceived source of competitive advantage. Cases A, D, F, G, I and K can be categorised under this group. Within supply chain integration, a cluster of cases refer to customer relationships as a key source, and a second cluster stresses the importance of working closely with suppliers. As previously noted, the roof truss manufacturer was at risk from a lack of suppliers for the plating which binds roof truss beams. The manufacturer stated that long term relationships with plate manufacturers and software providers were extremely important. The manufacturer of modular bathrooms highlighted that relationships with suppliers of critical components was essential for successful project delivery. The Brick and Block supplier stated that it was essential to have supply chain framework agreements in place with suppliers in order to deliver effectively to customers.

Cases A, G and I all alluded to the integration with customers as a source of competitive advantage. In the case of timber frame manufacturers, a team consisting of design, project and manufacturing staff were assigned for each client order in order so that different areas of the business could be integrated to deliver client needs. The company espoused the "partnership opportunity curve", which was articulated in company documents. This suggests that if the manufacturer is only involved in the construction phase of a project, or shortly before the start of construction, there is limited opportunity to add value. If the manufacturer is involved early on during planning approval, tender issue and project design stages, then it can advise on appropriate specification, cut costs, contribute to buildability, design out waste and minimise design risk and error. The lift manufacturer suggested that building close relationships with centralised purchasing contacts at major clients was critical to securing repeat business. The timber supplier argued that long term relationships can build a common understanding that helps to reduce the costs of transactions. The capabilities of suppliers can be harnessed for responding to volume, mix and new product changes. A "seamless supply chain" (Towill, 1997a), where information requirements are freely available on time and in undistorted form, captures a more accurate picture of customer requirements and facilitates quick response, improving delivery flexibility.

Source 3 - Information Technology Systems

Information technology (IT) systems were cited 3 times as a source of competitive advantage. Cases G and K both stressed the importance of bespoke IT systems as a source of advantage. In the case of the timber frame manufacturer, bespoke software interfaced with design software (such as CAD – Computer Aided Design) to facilitate integration of manufacture and design. This promoted 'design for manufacture' principles into the system. The bespoke IT system utilised by the modular bathroom manufacturer increases visibility and offered structure to different stages of the process. Case A, the lift manufacturer, used a global enterprise resource planning system. This helped the organisation maintain data integrity and availability across its different business units and activities. IT systems promote real-time visibility of demand information, thereby better allowing organisations in the supply chain to match capacity with demand. Real-time visibility of project progress and delivery date requirements would allow suppliers to be more proactive and flexible in changing due dates.

Source 4 - Logistics

It is also possible to gain an edge over competition through logistics capabilities. This was highlighted in cases B, D, I and K. Case D, the roof truss manufacturer, gains advantage from combining in-house transport capabilities with outsourced logistics. The in house capabilities include drivers and a fleet of different vehicles. Further vehicles are then shared between different product areas within the organisation. Contract transport and agency drivers are also used to meet any periods of high demand or urgency. The window manufacturer outsourced all of its logistics operations to a third party logistics service provider. Service level agreements are agreed and the logistics provider was able to offer stockholding either centrally, in northern Europe, or locally, at locations in the UK, if required. The paint subcontractor highlighted the advantages of consolidation centres for delivering into construction projects. Operational advantage was gained from the recently opened logistics and consolidation centre located near the M25 to serve London. This provided a controlled environment for inventory management and reduced reliance on inconsistent deliveries from large suppliers of standard paints.

Logistics capabilities have an impact on delivery and access flexibility. The strategic location of warehouses and consolidation centres, as well as the capabilities of the transport system, will affect the ability of a pipeline to provide a quick response to changing delivery due dates. Logistics capabilities will also determine the geographical spread that a supplier can offer to its customers.

Source 5 - Labour

Labour, in terms of getting the appropriate amount and skills, was identified as a source of advantage in cases J, K and L. The manufacturer of modular bathrooms highlighted the importance of a good project manager who can ensure that the work area has clear access and work can progress without interruption. Good site supervision and getting the right amount of people on site for site activity was a crucial advantage for the painting subcontractor, which used a flexible labour model to respond to project requirements. Whereas the company only employed around 80 employees, it could expand to over 200 through the use of subcontracted labour. The company organised a pool of flexible labour under the different skills required for paint work packages and contracts them on a flexible basis. In case L the dry-lining supplier emphasized the need to get people early on site and ensure good communications with site management.

A multi-skilled flexible work force supports the design of new products, and provides the flexibility to switch between different products. A flexible pool of labour facilitates volume flexibility as resources can be up scaled or downscaled in accordance with demand requirements. Finally, extra labour resources can be used to deal quickly with 'rush' orders in the case of changing due dates, thereby improving delivery flexibility.

Source 6 - Management Systems and Processes

Management systems and processes refer to the step by step methods and practices used to complete activities. These were cited on three occasions. Case A, the lift manufacturer, relies on process driven operations to overcome the complexity of its operations. In case J, the paint subcontractor proposed that its success was due to getting the right management systems and procedures in place using effective key performance indicators (KPIs) and standard operating procedures. Case B, the windows manufacturer, emphasized the processes and measures required for materials handling on site to reducing damages. The key enablers for effective management systems were KPIs and standard operating systems, which were associated with better information visibility and control, as well as standardisation and simplification.

Defined protocols for changing between products and new product design can support mix flexibility and new product flexibility. KPIs and control processes help to support volume and delivery flexibility, as they help to provide visibility of performance and potential control actions for fluctuations in demand and delivery. Delivery flexibility could also be improved by defined protocols for rush orders and project delays.

Source 7 - New Product or Process Innovation

New product and process innovation was cited in three of the cases. This refers to the development of new offering to customers in the form of new products or new and better ways of doing similar offerings. Cases A and C stressed the importance of new products. The pre-cast concrete manufacturer proposed that a secret concrete mix that offers a high strength to setting ratio, which sets very quickly and offers high strength and load bearing, is a major source of competitive advantage. The lift manufacturer distinguished itself from the competition with intelligent information systems and technology. The organisation invests large amounts of research and design in technology systems to remain ahead of competition. Case J highlighted the importance of process innovation. The paint subcontractor has developed a new off-site spray booth for off-site paint treatment, Biffa waste-safes and tin disposal facilities as well as new and specialist applications. New product and process innovation is intimately linked with new product flexibility.

Source 8 - Manufacturing Excellence

Many key texts in operations management and lean thinking make reference to manufacturing excellence (Hill, 2005; Slack et al., 2004; Womack and Jones, 1996; Womack et al., 1990). Manufacturing excellence was cited in two of the cases, B and G, as a source of advantage. Company B, the window supplier, described the importance of quality and reducing defects as an essential part of its competitive strategy. The timber frame manufacturer referred to automation of its factory and state of the art machinery as key to gaining an edge over competitors. This allows precision in manufacturing and design that competitors cannot match. A standard sized timber frame house can be manufactured in 45 minutes. The enablers of manufacturing excellence are automated factories using best practice principles along with flexible workshops. The combination of these two enablers can help deliver mass customisation (Pine, 1993). Manufacturing excellence helps to develop mix flexibility and volume flexibility. Single minute exchange of dies (SMED), a technique for minimising machine set up times, can reduce time taken to switch between products increasing mix flexibility (Gilmore and Smith, 1996). Capacity planning and evaluation techniques have also been linked with improved volume flexibility (Zorzini et al., 2008).

Source 9 - Modularity

Modularity involves product configurations that are obtained by mixing and matching sets of standard components (Salvador et al., 2002; Voordijk et al., 2006). Company K, the modular bathroom manufacturer, used a modular base, made from steel frame and wood panelling, with careful thought given to how this interfaces with different components. This acted as a core. High specification bespoke finishes were then added to this core. This approach combines the cost savings of generic standardised components with the service level of a customised finish. Company A, the lift manufacturer, also used modular design principles. Standard components and interfaces are used across and between product groups to enable cross product architectures. Assembly kits were delivered flat pack and the kits could be assembled with minimal labour and time on the construction site. Modularity helps companies to deliver mass customised products.

Modularity supports new product flexibility as many components can be re-used in new designs. It improves mix flexibility as it is easier to switch between existing products that have the same modular platform. Volume and delivery flexibility are improved as buffer stocks of standardised components combined with a customised finish offers the capabilities to cope effectively with fluctuations in demand and sudden changes in delivery requirements.

Source 10 - Flexible Organisational Structure

Finally, a flexible organisational structure was highlighted by two of the cases, J and H. This refers to the ability to shrink or grow an organisation with little penalty in time or cost. In case J, the paint subcontractor employed a minimal overhead strategy. Fixed overheads were never put at risk, and variable overheads could grow or shrink to match the order book. The organisation kept a pool of self employed labour on its books which it called upon when demand was high. Logistics was also outsourced. In the case of H, the door manufacturer, buying and selling strategic acquisitions in response to market requirements was seen a key capability. This included buying competitors and selling off business units or assets when the time is right. The enablers for a flexible overhead structure are investment in capacity and capabilities, flexible outsourced labour and a low overhead structure. This type of organisational structure supports volume flexibility.

6.6 RECOMMENDATIONS FOR PIPELINE IMROVEMENT

This final section seeks to assemble and synthesize the findings from the pipeline survey, and to relate these findings to the relevant literature. The synthesis is structured using four different recommendations for pipeline improvement. The recommendations are: reduce uncertainty by addressing the problems in the pipeline, strive for shorter and more consistent lead times, consider the sources of competitive advantage in pipeline improvement strategies and work together to improve pipelines. These recommendations are now discussed in turn.

1. *Reduce uncertainty by addressing the problems in the pipeline*

The problems that companies experience in the pipeline have been investigated in the pipeline survey. Ten problems in the pipeline have been identified and have been ranked according to the frequency that they were experienced in different pipelines. The 10 generic pipeline problems were identified which are as follows and are listed with the frequency that the problem occurred in the pipeline survey shown in brackets after each source: design changes/incorrect specification (6), establishing site readiness (5), labour shortages (4), information exchange (4), supply risks (3), integration of related trades on site (3), access issues (2), excessive product variation (2), payment and chains of custody (2), and tender uncertainty (2). A causal model was presented which illustrates the causes of these problems and potential solutions. The solutions to these problems are now summarised and related back to the structured literature review in chapter 2.

- *Information management.* A greater degree of information transparency has been proposed as a fundamental concern for effective supply chains (Mason-Jones and Towill, 1997). It is also important for developing agile supply chains (Christopher, 2000; Goldman et al., 1995). The structured literature review identified 15 papers investigating information management as a strategy for improving ETO supply chains. The analysis of pipeline activities that feed into ETO supply chains presented in this chapter suggests that better information management would address some of the problems experienced by the cases described herein. More specifically, project visibility for suppliers and manufacturers would enable them to establish site readiness for deliveries more effectively. The use of IT systems may help to facilitate information exchange and visibility throughout the pipeline.
- *Supply chain integration.* The structured literature review in chapter two identified 22 papers related to supply chain integration in ETO supply chains. The causal modelling presented earlier in this chapter suggests that collaborative forecasting and early supplier involvement in the design process are solutions to uncertainty and problems in the pipeline. It also suggests that proactive communications and early conditioning and familiarisation for areas of the supply chain that must work together on site are important to facilitate integration across the pipeline.
- *Flexibility.* Twelve papers that link flexibility with ETO activities were identified in part 2 of the literature. The causal relationships highlighted suggest that product flexibility, delivery flexibility, flexible labour models and communications flexibility are potential solutions to the problems in the pipeline.

2 *Strive for shorter and more consistent lead times*

Short and consistent lead times from manufacturers and suppliers are important in delivering the flexibility and agility requirements of ETO supply chains. The results of the pipeline survey suggest that longer lead times are more variable, and the most of the variability is located at the design stage. The obvious route is to move toward greater simplicity and to re-engineer processes so as to reduce lead times and increase consistency.

Reducing variability and lead times in the design and approval stage would reduce significantly the overall length and uncertainty of order to delivery pipelines. In part 2 of the literature review, nine papers were categorised under the 'time compression' category, suggesting that time compression should be adopted in ETO supply chains. The results of this chapter supports these papers, proposing that time compression is an important objective for improving pipelines that feed into ETO supply chains.

3. *Consider the sources of competitive advantage in pipeline improvement strategies*

This chapter has investigated the sources of competitive advantage in the pipeline. The sources of advantage for the focal companies in pipelines were analysed, identifying 10 sources. They are listed as follows, with the frequency that the source occurred in the pipeline survey shown in brackets after each source: specialist expertise (6), supply chain integration (6), information technology systems (3), logistics capabilities (3), labour (3), management systems and processes (3), new product and process innovation (3), manufacturing excellence (2), modularity (2) and a flexible organisational structure (2).

A company can also consider re-engineering its operations by forward or backward shifting through supply chain structures for strategic benefit by shifting the decoupling point. Moving the decoupling point further toward the STS structure may help to reduce the delivery lead time to customers and to increase manufacturing efficiency, while moving the decoupling point backwards toward the ETO structure shift may help to increase the knowledge of customer orders at the time of production (Olhager, 2003). An assessment of the appropriate amount of customisation and product variety, and hence flexibility, to offer to the customer is important in developing an appropriate supply chain structure.

4. *Work together to improve pipelines*

The analysis of problems in the pipeline highlights the need for a collaborative, holistic approach to pipeline improvement. The solutions to the problems highlighted often require network co-ordinators to work together to improve flows of information and integrate processes. In some cases they also require different suppliers within the project supply chain to work together more effectively. The success of an ETO project will rely heavily on the ability of a responsive "extended" enterprise. This analysis has illustrated that Companies must work together develop responsiveness. Different relationship strategies are addressed in more detail in the next chapter, but this chapter has highlighted the role of the following in improving pipelines:

- More consistency from clients and contractors in purchasing and managing collaborative frameworks would help suppliers and subcontractors to predict demand levels and to manage their operations in more effective and efficient ways;
- Proactive communication between different members of the supply chain would support shorter and more consistent lead times. IT systems that allow visibility of information between different members of the supply chain would help to enable more responsive pipelines;
- Supplier training and improvement by network co-ordinators would help to develop the required capabilities and improve pipelines.

6.7 DISCUSSION AND STATEMENT OF CONTRIBUTION

This chapter has addressed the specific gap identified whereby the partnership and pipeline literature for construction supply chains has placed too much emphasis on client relationships, as oppose to those that might arise upstream between contractors and their suppliers (Dainty et al., 2001a; Dainty et al., 2001b; Ireland, 2004; Proverbs and Holt, 2000). In addition, much of the research on pipelines has been conducted in high volume manufacturing sectors (Aitken et al., 2005).

The importance and contribution provided by this chapter can be summarised as follows:

While the client-main contractor relationship has been well researched in the construction sector, the relationship between main contractors and subcontractors has not been well researched. Furthermore, pipeline research has focused primarily on high volume, stable supply chains. This chapter has addressed this gap by providing an empirical investigation of pipeline activities between two network co-ordinators and 12 suppliers within the construction industry. The problems and sources of competitive advantage were identified within these pipelines, and recommendations are made for pipeline improvement.

6.8 CONCLUSION

In the context of ETO systems, this chapter has specifically addressed the research question 'How can organisations improve pipelines in ETO supply chains?' At the start of the chapter, the generic activities in the pipeline were identified. Enquiry, design, approval, procurement, manufacture, transport and site integration phases were discussed. Analysis of the pipeline survey has shown that lead-times associated with the design stage are the most variable. The pipeline survey also indicates that as lead-times get longer they also get more variable. The findings of the pipeline survey also highlight the diversity of operations that feed into an ETO project. A range of supply chain structures must be managed to successfully deliver an ETO project.

In addition to analysing the generic pipeline activities and their lead-times, the main problems in the pipeline have been investigated in this chapter. Ten generic pipeline problems were identified, which are as follows and are listed with the frequency that the problem occurred in the pipeline survey shown in brackets after each source: design changes/incorrect specification (6), establishing site readiness (5), labour shortages (4), information exchange (4), supply risks (3), integration of related trades on site (3), access issues (2), excessive product variation (2), payment and chains of custody (2), and tender uncertainty (2). A causal model was presented which illustrates the causes of these problems and potential solutions.

The sources of advantages for the focal companies in pipelines were also analysed, identifying 10 sources. They are listed as follows with the frequency that the source occurred in the pipeline survey shown in brackets after each source: specialist expertise (6), supply chain integration (6), information technology systems (3), logistics capabilities (3), labour (3), management systems and processes (3), new product and process innovation (3), manufacturing excellence (2), modularity (2) and a flexible organisational structure (2). The benefits of these different approaches are illustrated using a causal model.

The synthesis in the final part of the chapter develops four recommendations for pipeline improvement. The recommendations are: reduce uncertainty by addressing the problems in the pipeline, strive for shorter and more consistent lead times, consider the sources of competitive advantage in pipeline improvement strategies and work together to improve pipelines. The next chapter addresses the last recommendation in more detail, exploring different relational categories that a network co-ordinator can use to optimise the network of suppliers in ETO projects.

SUMMARY OF CHAPTER 6 AIMS

1. **Rationalise and investigate supply chain flexibility in the ETO sector**
   - A conceptual model of supply chain flexibility has been developed and explored through the case research.
2. **Develop a purchasing model for engineer-to-order supply chains**
   - A purchasing model consisting of 3 tiers of supplier has been developed including approved suppliers, preferred suppliers and strategic partners
3. **Integrate supply chain flexibility concepts with a purchasing model**
   - The dimensions of supply chain flexibility were integrated with the 3 tiers of suppliers. High levels of vendor flexibility can be achieved through strategic partnerships and sourcing flexibility can be achieved with approved suppliers
4. **Consider the role of supply chain flexibility in mitigating project uncertainties**
   - A mapping exercise was conducted, which concludes that vendor and sourcing flexibility can be used to mitigate 23 of the 42 uncertainties

CHAPTER 7

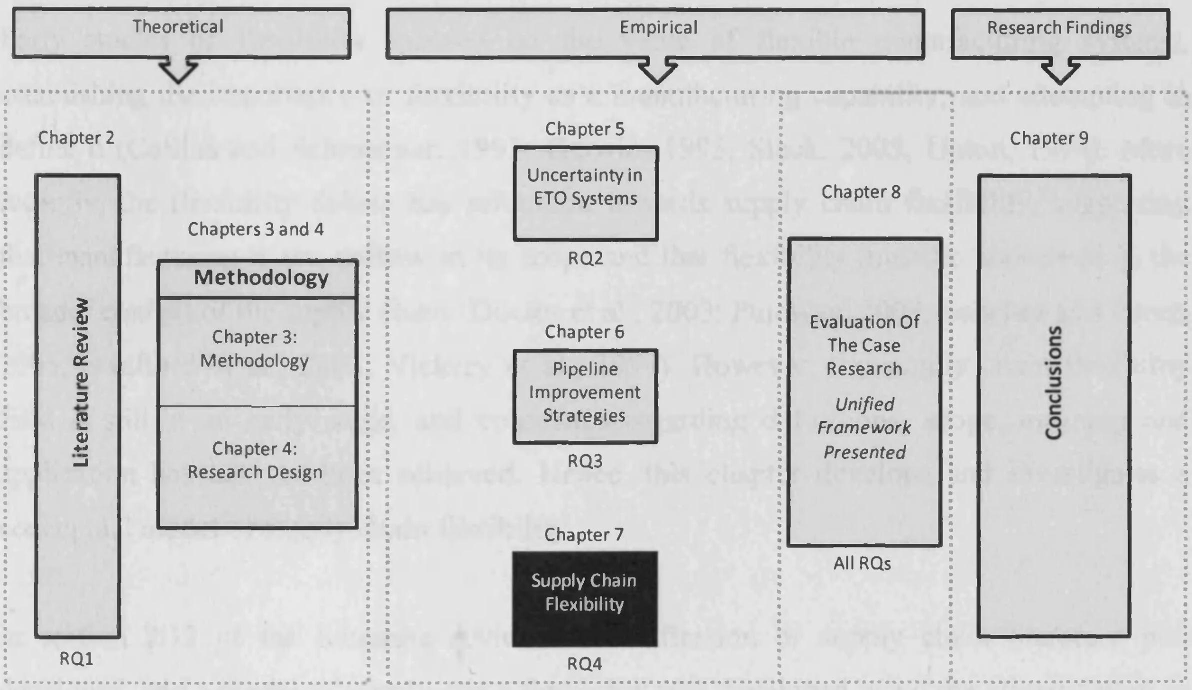
ACHIEVING FLEXIBILITY IN ENGINEER-TO-ORDER CONSTRUCTION SUPPLY CHAINS

CHAPTER 7 AIMS

1. **Rationalise and investigate supply chain flexibility in the ETO construction sector**
2. **Develop a purchasing model for engineer-to-order supply chains**
3. **Integrate supply chain flexibility concepts with a purchasing model**
4. **Consider the role of supply chain flexibility in mitigating project uncertainties**

RESEARCH QUESTION ADDRESSED

RQ4: How can flexibility be rationalised in ETO construction supply chains?



7. INTRODUCTION

The literature review established flexibility as an important strategic capability for companies and supply chains to achieve. The development of supply chain flexibility is of particular importance when developing an agile supply chain in uncertain market conditions. Sanchez and Perez (2005) conducted a survey of 126 Spanish automotive firms and found a positive relation between a superior performance in flexibility capabilities and firm performance. Oke (2005) supported this and suggested that flexibility can be a major competitive weapon, but noted that it is a complex, multidimensional construct. Dreyer and Gronhaug (2004) argued that it is important to identify the types of flexibility so that can be matched with uncertainties faced by a supply chain. The importance of identifying flexibility types and the sources of flexibility has been noted by a number of authors (Dreyer and Gronhaug, 2004; Koste and Malhotra, 1999; Naim et al., 2006; Slack, 2005).

Early studies of flexibility focused on the value of flexible manufacturing systems, establishing the importance of flexibility as a manufacturing capability, and attempting to define it (Collins and Schmenner, 1993; Gerwin, 1993; Slack, 2005; Upton, 1994). More recently, the flexibility debate has refocused towards supply chain flexibility, suggesting that manufacturing is too narrow in its scope and that flexibility must be conceived in the broader context of the supply chain (Duclos et al., 2003; Pujawan, 2004; Sanchez and Perez, 2005; Swafford et al., 2006; Vickery et al., 1999). However, the supply chain flexibility field is still at an early stage, and consensus regarding definitions, scope, meaning and application has not yet been achieved. Hence, this chapter develops and investigates a conceptual model of supply chain flexibility.

In section 2.13 of the literature review a classification of supply chain literature was developed, and a model of supply chain flexibility was developed using the classification as a foundation. The model is reprinted in figure 7.1 to provide a reminder for the reader. It is investigated via the case studies throughout this chapter.

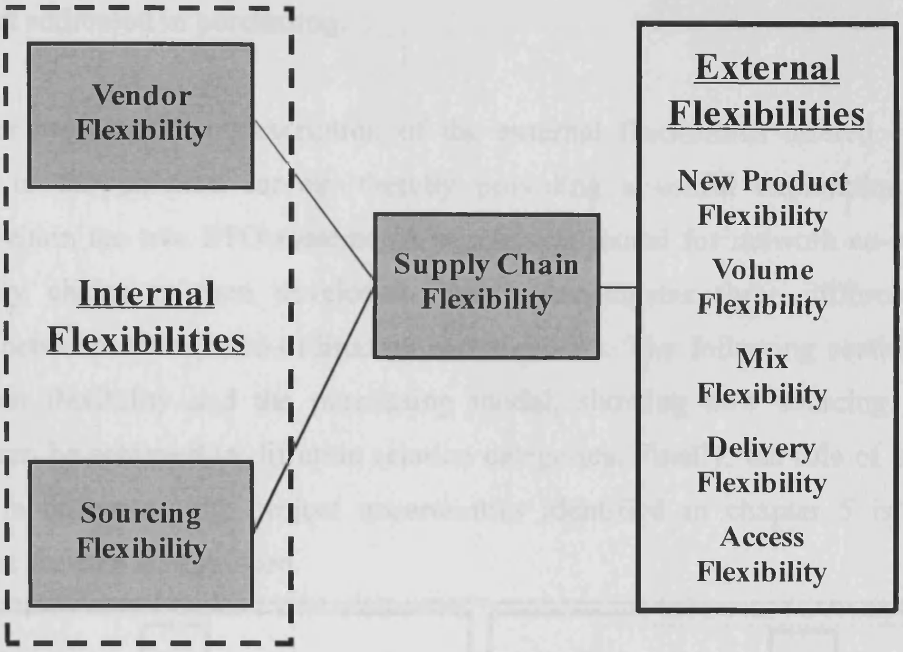


Figure 7.1: Conceptualisation of supply chain flexibility

This model proposes the antecedents of vendor and sourcing flexibility. Vendor flexibility was defined as the specific types of flexibility relating to individual vendors that support manufacturing, warehousing or transport operations. Sourcing flexibility was defined as the ability to reconfigure a supply chain network through the selection and de-selection of vendors. This model is investigated within the empirical setting of the two ETO Construction systems. Figure 7.2 shows that this chapter draws from data collection activities from all units of analysis studied in the thesis.

This chapter examines how supply chain flexibility can be achieved in the ETO sector, where high levels of uncertainty arise from project specific demands. The strategic partnering approach to supply chain management has been promoted by researchers (Akintoye et al., 2000; Beach et al., 2005; Bresnen and Marshall, 2000; Cox and Thompson, 1997; Ireland, 2004) and UK government reports (Latham, 1994). However, in a sector dominated by projects, often varying in frequency, scope and scale, strategic partnerships need to be considered vis-à-vis flexibility requirements. A range of portfolio models have been proposed in the literature in order to support purchasing decisions and supplier selection (Cox and Thompson, 1997; Kraljic, 1983), but the role of supply chain flexibility has not been addressed in purchasing.

The chapter begins with a description of the external flexibilities offered by the focal companies in the pipeline survey, thereby providing a useful exploration of vendor flexibility within the two ETO systems. A purchasing model for network co-ordinators in ETO supply chains is then developed, which investigates three different relational categories between network co-ordinators and suppliers. The following section integrates supply chain flexibility and the purchasing model, showing how sourcing and vendor flexibility can be achieved in different relation categories. Finally, the role of supply chain flexibility in mitigating the project uncertainties identified in chapter 5 is considered. Conclusions are then summarised.

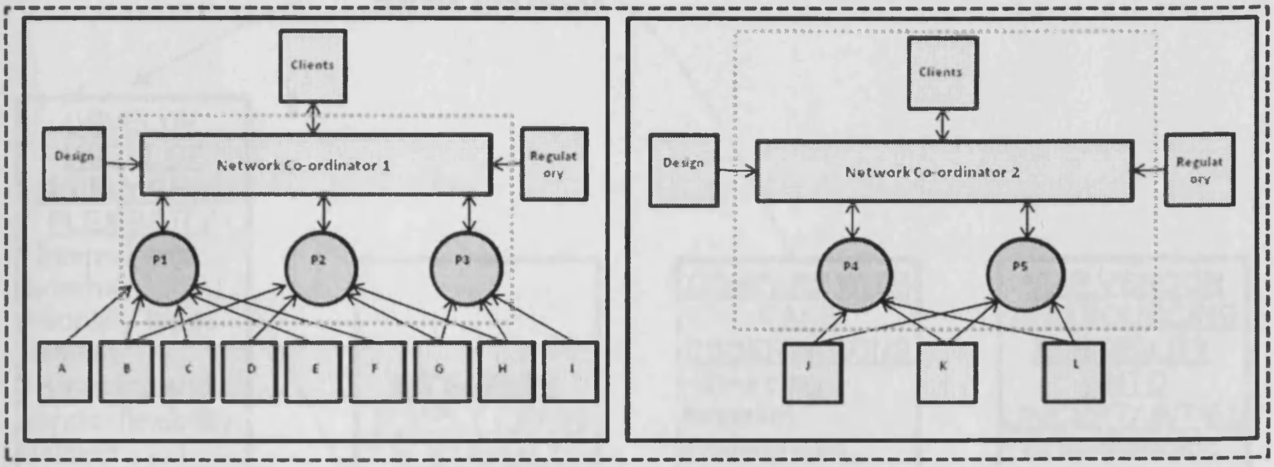


Figure 7.2: The two ETO systems and the focus of the chapter 7

7.1 METHOD OVERVIEW

This chapter draws from data collected from all three units of analysis. The flow of research activities for the chapter is shown in figure 7.3. It shows that a model of supply chain flexibility and a purchasing model are developed iteratively using literature and observations from the case research. As noted by Eisenhardt (1989), the constructs, questions, definitions and measurements in case study research often emerge from the analysis process itself rather than being specified a priori. Emergent relationships between constructs are also confirmed, revised or disconfirmed as case study research progresses.

Emergent concepts, observations and findings in this chapter were compared with enfolding literature as the research progressed.

The first antecedent of supply chain flexibility investigated in this chapter is vendor flexibility. Recall that five external flexibilities were defined in the literature section: new product, mix, volume, delivery and access flexibilities. The external flexibilities offered by the supplier pipelines included in this study were ascertained through the pipeline survey, including the factory visits and supporting information gathered from the websites of suppliers.

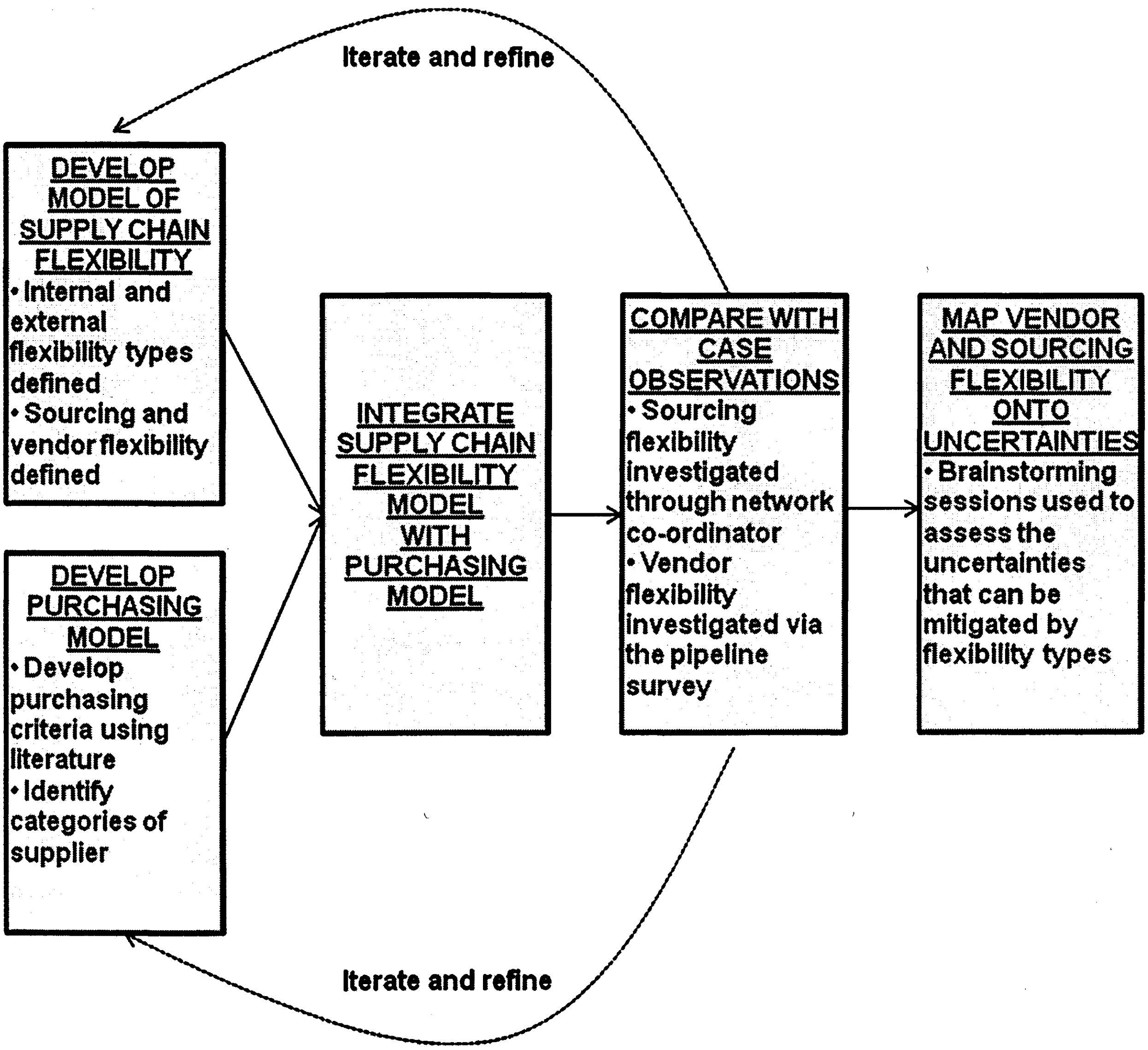


Figure 7.3: Flow of research activities in chapter 7

A purchasing criterion was then developed from the literature and iteratively compared with the behaviour of network co-ordinators in the two systems. This was achieved through in depth interviews with the network co-ordinators regarding purchasing processes and systems. The industrial secondment facilitated this iterative process. The three categories in the purchasing model were developed as a result of this iterative process. Supply chain flexibility antecedents were then integrated with this model and compared with the behaviour of network co-ordinators. Finally, antecedents of supply chain flexibility were then mapped onto the 42 uncertainties identified in chapter 2 to establish the role of supply chain flexibility in mitigating uncertainties. Brainstorming sessions were used to confirm the accuracy of this mapping exercise.

7.2 VENDOR FLEXIBILITY

Before the issue of sourcing flexibility is investigated, this section will explore the flexibilities offered by suppliers. In the literature review chapter, vendor flexibility was defined as the specific types of flexibility relating to individual vendors that support manufacturing, warehousing or transport operations. This section summarises the external flexibilities offered in the 12 case pipelines, and provides a foundation for a later exploration of how vendor and sourcing flexibilities can be combined to achieve different levels of supply chain flexibility.

7.2.1 Pipeline A – Elevator Manufacturer

New Product Flexibility – Information systems and technology were a big differentiator for company A. Around 5-10% of business required completely new engineering work. These projects often involve large scale commercial developments with unique layouts that are linked via intelligent systems.

Mix Flexibility – The majority of elevators utilised standardized options for customers. A typical residential elevator, for example, offered a range of finishes, colours, capacities, dimensions, doors, panels lighting, rails and controls.

Volume Flexibility – Production volumes were forecasted 6-12 months ahead to ensure that capacity can meet demand requirements. The forecasts were based on relationships with clients, monitoring of construction investment and construction levels in different markets, and an analysis of which organisations are winning tenders. This type of forecasting is accurate within +/-10%.

Delivery Flexibility – Delivery, in the case of elevators, also included the task of installation, which can take up to 4-6 weeks. Due to delays on site, storage for clients was commonplace and flexible labour installation plans must be revised daily. Key standardized modules and parts are held locally and centrally to help respond to urgent new installations or service requirements.

Access Flexibility - With international operations, Company A was able to offer almost global coverage. Parts are consolidated in mainland Europe, where an in-house logistics function manages logistics.

7.2.2 Pipeline B – Window Manufacturer

New Product Flexibility – While many windows are produced to order, very few are offered to the customer on an engineer-to-order agreement with new designs.

Mix Flexibility - Customers were offered a wide range of standard choice for windows, including a variety of colours, sizes, locking mechanisms, acoustics, ventilation systems, sills, restrictors and glazing. Finished goods were held for the Swedish market, where the manufacturing is based, and products for the UK are typically made-to-order.

Volume Flexibility – Different quantity requirements can easily be built onto the planning system unless it is a very large project, which might increase the lead time.

Delivery Flexibility – In addition to delivery, installation for windows was also offered as a service by company B. Gangs of labour can install 40-50 windows per week into a building if required. Logistics was outsourced to a third party who can rush through orders or offer stockholding either centrally, in northern Europe, or locally, at locations in the UK, if a due date is too early for a project.

Access Flexibility – A third party logistics provider offered coverage of the UK and most of Europe.

7.2.3 Pipeline C - Pre Cast Concrete Manufacturer

New Product Flexibility – Typically, each order had unique fixing and hole penetration points. Pre-cast concrete also usually required unique dimensions for different projects, which are subject to a maximum and minimum. Special requests were considered on a project by project basis.
Mix flexibility - A range of standard depths for pre-cast concrete were offered which are set in 5mm increments. Widths and lengths could be cut to order, but a maximum is placed on both dimensions. Company C also offered design, stock holding and installation services.
Volume flexibility – If the order book was full it was very difficult to increase volume at short notice as the manufacturing capacity is constrained by concrete pouring space.
Delivery flexibility – When pre-cast concrete is delivered, plant and labour are both required on arrival to install flooring directly into location on site. In the case of rush orders it was possible to reduce the manufacturing lead time down to two weeks, but labour and plant must be available for site installation to make this worthwhile.
Access flexibility – Due to the size and difficulty of transporting concrete most of the market was in the south of the UK.

7.2.4 Pipeline D - Roof Truss Manufacturer

New Product Flexibility – Roof trusses were rarely based on completely new designs, but mix or reuse pre-existing designs for different orders. Designs varied depending on size, preferred style and construction method. Plating systems, which were used to bind the timber together, were the main obstacle to new product development. They are usually tied in with design software, and are only available from a small number of suppliers in the UK.
Mix Flexibility – For the majority of orders, Company D received sizes and designs from design consultants and then designed the roof trusses within these guidelines. Most of these drawings were based on existing designs. No installation service were offered.
Volume Flexibility – Very large orders required a one or two week notice period.
Delivery Flexibility – Company D could hold around two weeks worth of stock on site. Extra stock could be called off on a short lead time unless there are very large volumes.
Access Flexibility - 75% of business was in London or the south of the UK with rest being

in the Midlands or the South West of the UK.

7.2.5 Pipeline E - Metalwork Subcontractor

New Product Flexibility – Company E responded to metalwork design requirements that are produced by design consultants and either responded with a competitive bid for the work or rejects the work if it is unsuitable. The company was unable to offer any design support services.

Mix Flexibility – Small design changes, which were fully specified by drawings, could be accommodated. A wide range of metalwork products were also offered, including structural steel, architectural steel, balustrading, handrails, sheet metalwork and metal decking.

Volume Flexibility – Company E operated from a small site in the South East of the UK with limited space. Volume flexibility was, therefore, limited. The flow of make-to-order and buy-to-order products needed careful management to overcome these capacity constraints.

Delivery Flexibility – Due to the small premises there was limited space to hold stock. Once items were produced there was little flexibility to hold these in storage in the case of project delays. Most items, however, could be held on site.

Access Flexibility – Company E targeted the south east of the UK as its primary market.

7.2.6 Pipeline F - Brick and Block Supplier

New Product Flexibility – New designs and technical specifications were difficult and expensive to implement but Company F was willing to liaise with raw material suppliers, manufacturers and designers to deliver such requirements.

Mix Flexibility – A standardised list of brickwork, based on aesthetic, technical specifications and cost, was offered to customers. Company F acted as an agent among construction companies, manufacturers and design consultants, to encourage all parties to agree on a package that will have an overall cost, finish and specification to meet the needs of all stake-holders.

Volume and *Delivery Flexibility* – Working stock availability at manufacturing locations determined the degree of delivery and volume flexibility. For more standardised bricks,

Company F was able to search for available product from a range of manufacturers or stockholders to satisfy late delivery or volume changes.
Access Flexibility – With 24 sites in the UK, Company F offered coverage throughout the UK.

7.2.7 Pipeline G - Timber Frame System Manufacturer

New Product Flexibility – The timber frame system manufacturer offered the opportunity to work with clients at every stage of a new project and was willing to enter into new sectors for application of timber frame technologies. The company offered concept design and detailed design services, as well as manufacture, delivery and erection. The automated factory was very flexible, but if this was unable to meet a specification the company had a bespoke workshop and skilled joiners to manage bespoke requirements. Bespoke joinery, windows, plasterboard and insulation requirements could also be discussed as part of a package.
Mix Flexibility – A range of acoustic and thermal performance, specifications and finishes were offered. Machine settings could easily be changed to cope with size variations. Automated machinery integrates with design software which automatically programmes different specifications into the manufacturing system. Orders were relatively large; orders of 10 homes or less were not taken on, so manufacturing was often batched. The company also offered wide sector coverage and has experience of building hotels, housing, leisure centres, student accommodation and care homes.
Volume Flexibility – The total yearly output for the company was approximately 12,000 units. The requirements for a house could be manufactured in 45 minutes.
Delivery Flexibility – A mixture of in-house and outsourced logistics was used to meet delivery requirements. These were usually staggered across a few weeks at regular intervals on larger projects. Typically, transport was on a 1 or 2 day lead-time, but delivery requirements were planned in advance and phased to suit build plans. There is a large stock yard at the factory, which could be used if a project was delayed.
Access Flexibility – The focal company had 2 major manufacturing sites in the UK, offering UK wide coverage.

7.2.8 Pipeline H – Door Manufacturer

New Product Flexibility – Whereas the company did not offer customers the opportunity to directly impact the design process, the company was planning to launch a 'design your own door' online facility, which would allow customers to pick from a wide range of standardised options and visualise the final product online.
Mix Flexibility – Three basic product groups were offered: glass reinforced polyester (GRP), eco frame and steel doors. Within the GRP group 10 door styles were offered, in a range of colours, with a choice of glazing including clear, bevelled and patterned. A selection of hardware and furniture doors options were offered, including letter plates, eye viewers, security chains and locks.
Volume Flexibility – Batch orders for projects were made-to-order. Capacity was allocated according to the order book and due dates for project requirements. Some standardised lines were made to stock and were delivered to retailers in high volumes. The demand for standard lines was predictable, so spare manufacturing capacity was held for batch project orders. The total manufacturing capacity was 600 doors per week.
Delivery Flexibility – Deliveries were usually consolidated into economic loads and route plans. This tended to add a little to the delivery lead time, which had a most likely time estimate of 7 days.
Access Flexibility – The focal company had 1 major manufacturing site in the UK, which offered UK wide coverage.

7.2.9 Pipeline I - Timber Supplier

New Product Flexibility – Timber was treated based on standard designs and processes, but engineered timber solutions and bespoke designs, as well as more complex assemblies, such as roof trusses, were offered. A quote was promised in 5 working days. The focal company was also willing to set up an 'outsource store', which could be devoted to a particular customer or site and thereby act as a consolidation point for a range of products.
Mix Flexibility – A range of different treatments, species of timber and expected service life options were offered. The company could advise based on customer requirements. Such advice depended on the exposure of timber to moisture and weather conditions, and if

timber would be above or below ground level. Much of the treated timber was held in stock and could be cut to size at a local store.

Volume Flexibility – The focal company was the largest importer of timber into the UK, so even very large orders could be accommodated very easily and quickly. A stock management system was used to co-ordinate deliveries; bulk deliveries could be delivered direct from treatment centres and timber mills to site.

Delivery Flexibility – Logistics was managed in-house. The focal company could offer frequent daily deliveries direct from a local store to a site, or large bulk deliveries could be offered direct from a treatment centre.

Access Flexibility – The builders' merchant had over 500 branches across the UK, with 3 main distribution and processing centres.

7.2.10 Pipeline J - Spray and Painting Subcontractor

New Product Flexibility – Approximately 80% of the business was general applications, with 20% specialist applications. The focal company in this pipeline was able to develop and discuss specialist effects with clients, such as stone, marbling, graining, colourwash, antiquing, dragging, sponging and speckling. It was also able to undertake specialist artwork finishes to large areas of wall to create murals and illusions.

Mix Flexibility – General applications could include airless spraying of very large areas of walls and ceilings. A large range of coatings were available, including fire and other protective coatings.

Volume Flexibility – The focal company was able to accommodate contracts that value from £5,000 to £5 million. Through a pool of flexible skilled labour and site managers, the workforce could be enlarged dramatically to suit the needs of a project. The company could deploy 200 plus operatives on a project if required.

Delivery Flexibility – Flexible deliveries were made possible by a consolidation centre on the outskirts of the M25. This allowed a 'milk round' of deliveries to different sites in the South East. The company had its own fleet of vehicles for outbound deliveries from the consolidation centre, but most of the inbound deliveries were made by the large standard paint manufacturers. Deliveries could be rushed to a certain site if required or, if a project was delayed, stocks of paint could be held at the consolidation centre.

Access Flexibility – The company offered general applications across the South of the UK, but covered the whole of the UK for specialist applications.

7.2.11 Pipeline K - Modular Bathroom Manufacturer

New Product Flexibility – the focal company had over 20 in-house design technicians that were able to create new designs, take architectural drawings and convert them into detailed working drawings. The team could produce 3D modelling to clients to visualise new designs.

Mix Flexibility – The factory could accommodate timber from rough sawn boards through to detailed veneering, finishing and assembly. The company used a patented modular technique, which is an adaptive walling system that could be manufactured to any size due to flexible interfaces. It could be manipulated to suit site access and forms a base to which a final face finish could be applied. This was all undertaken offsite so that a delivery of walling units to site provided a series of modules ready for simple installation by minimal labour.

Volume Flexibility – Capacity at the time of writing allowed for a minimum of 600 wall modules per week.

Delivery Flexibility – If the factory was not running at capacity, delivery dates could be moved forward. There was plenty of storage at the factory if a project was delayed. Transport was outsourced.

Access Flexibility – The focal company had two large manufacturing facilities in the UK. It offered UK wide coverage. Approximately 50% of business was in the South East with the rest of UK accounting for the other 50%.

7.2.12 Pipeline L – Drylining and Safety Systems Subcontractor

New Product Flexibility – Technical designs or drylining systems were largely fixed, and dominated by very large suppliers such as British Gypsum and Lafarge. The focal organisation added value by advising clients on the right product to use on a project to minimize the cost. The company could also work with clients to offer bespoke packages of fire and safety services to be installed with the drylining.

Mix Flexibility – Installation of all major drylining systems was offered. This includes metal stud partitions, shaftwall, wall linings, plastering, tape and joint finishes and light steel framing techniques. This could be combined with fire safety systems for a complete fire safety package. Any steel and metal work was manufactured in-house in a flexible workshop.

Volume Flexibility – Drylining, unless for a very large project, could usually be purchased from working stock from one of the large suppliers. The in-house metal workshop was only a small support service and struggled to maintain requirements for large projects.

Delivery Flexibility – The focal company had to rely on large suppliers for deliveries of drylining. For small projects, the manufacture and delivery of in-house metalwork was very flexible.

Access Flexibility – A UK wide service was offered.

7.3 A PURCHASING MODEL FOR ENGINEER-TO-ORDER SUPPLY CHAINS

A range of purchasing models have been addressed in the literature review (Cox, 2009; Kraljic, 1983; Olsen and Ellram, 1997). The purchasing model developed herein builds on these models. It is specifically tailored for the ETO supply chain, and purchasing criteria from the different models are integrated to fulfil the requirements of project industries. It has been developed iteratively, using both criteria from academic literature and using empirical observations. Dimensions from Cox (2009), Ireland (2004) and Kraljik (1983) are used. Practical guidelines from constructing excellence are also included. The contribution from these sources will be explained more fully later in the section.

Both of the network coordinators in the study organize their supply chain by categorizing suppliers into three different tiers. While the terminology in the two different case companies differs slightly, in this thesis they are categorised as approved suppliers, preferred suppliers and strategic partners. These categories were used to inform sourcing and procurement decisions for different projects. 'Approved' status refers to suppliers and subcontractors that have filled in a questionnaire, where health and safety standards have been inspected, and where the organisation has been vetted with references. 'Preferred' status builds on this layer and is granted when an organisation successfully completes a number of projects and delivers consistently on KPIs. A 'strategic partner' is a formal recognition of a partnership and includes agreements on tender assistance services, resource management and availability, environmental performance, collaborative working, training, and performance measurement and review. Strategic partners help to streamline contractual arrangements for individual projects, and help suppliers to achieve a more stable demand pattern.

In System 1, the main contractor held a database of around 750 suppliers and subcontractors. Seventy of these were recognised as strategic partnerships, 180 were recognised as preferred contractors and 500 were approved suppliers. In System 2 there were 30 strategic partners, 90 preferred and 180 approved suppliers. Both case companies allowed suppliers to progress through the different categories as long as they met the criteria. KPIs were managed by a supply chain manager and regular reports were produced examining KPI figures.

This model is developed further by mapping the criteria outlined in the purchasing literature review onto these different supplier categories. The following dimensions of purchasing are identified as important for project purchasing in the literature review:

- Criticality – The criticality of the output of a supplier or subcontractor to project success. Some products or services will have significant implications for cost and time if they fail (Constructing Excellence, 2003).
- Regularity of demand – the extent to which demand is one off or project specific or high volume and applies to a number of different projects (Ireland, 2004).
- Spend – This is used to refer to the proportion of total procurement or relative cost spend that a service, supplier or subcontractor accounts for (Constructing Excellence, 2003).
- Degree of supplier involvement and development – This refers to the extent to which the buying organization proactively develops supplier capabilities and collaborative relationships (Cox, 2009).
- Supply Risk –This refers to the extent of monopoly or oligopoly conditions, entry barriers, the pace of technological advance and complexity of the products (Kraljic, 1983).

Figure 7.4 shows the different categories and the criteria taken from the literature. Strategic partners should be selected based on a number of criteria. The product or service should have a high regularity of demand across different projects rather than a one-off transaction. The product or service should be critical for the success of different projects and should account for a high proportion of supply spend. A further rationale for a strategic partner is high supply risk. There may be few suppliers of a particular product or service on the marketplace. Finally, the supplier must have an excellent track record of performing on KPIs. Network co-ordinators consider investing resources to develop suppliers in this category.

Preferred suppliers should also be categorised according to robust criteria. The demand for the particular product or service may not be as regular as for the strategic partner category and may not be as critical for the project success. The product or service would account for less spend than the previous category. Products may be critical or non critical and may pose a moderate supply risk. Network co-ordinators invest resources in suppliers in this group only if they consider them to be progressing towards the strategic partner group. Finally, approved suppliers are those where the demand for the good or service are low, and perhaps even for a one-off project or purchase. These would typically be for non-critical products, which account for a low proportion of spend and pose very little supply risk.

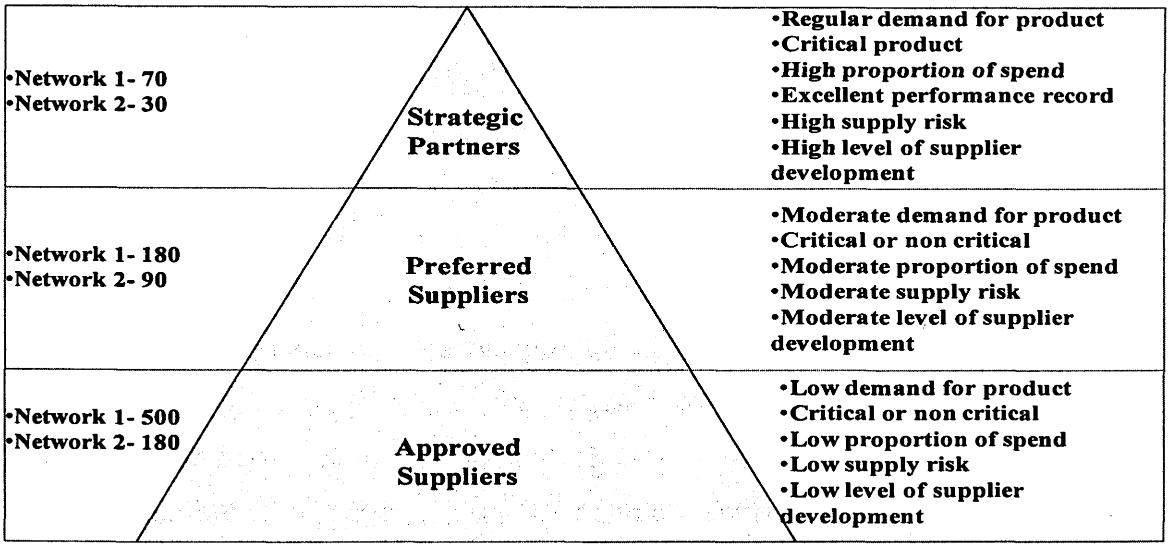


Figure 7.4: A purchasing model for engineer-to-order supply chains

The purchasing model proposed in figure 7.4 has been developed from industry, using case studies from the two network co-ordinators, and from the purchasing literature, using pertinent papers to develop robust criteria to map onto the model. Flexibility has not been investigated in depth as a consideration in purchasing behaviour, and is not considered in the industry case studies. The next section explores how supply chain flexibility might be integrated into this purchasing model.

7.4 INTEGRATING SUPPLY CHAIN FLEXIBILITY AND PURCHASING

In the literature review, sourcing flexibility was defined as the ability to reconfigure a supply chain network through selection and de-selection of vendors. Figure 7.5 shows a matrix illustrating the proposed supply chain flexibility implications for different supplier categories. The diagonal line running through the matrix shows three different relationship categories between buyer and supplier. Along the axis the matrix shows the level of sourcing and vendor flexibility associated with each relationship type. The supplier categories propose an ideal fit for achieving flexibility. If the supply chain moves towards the top left of the matrix, utilising high levels of vendor flexibility and high levels of sourcing flexibility, then there is an over-compensation for risk and uncertainty. Hence, the supply chain is burdened with unnecessary cost. If the supply chain moves toward the bottom right of the matrix, utilising low vendor flexibility and low sourcing flexibility, then the supply chain may be under-prepared for risk and uncertainty. The remainder of this section will describe in more detail the relationship of different supplier categories with supply chain flexibility.

7.4.1 Strategic Partners

Strategic partnerships demonstrate recognition of the benefits of the strategic partnering approach where strategic suppliers are selected for key elements, or work packages, delivered by the supply chain. In the network co-ordinator case studies, this category had the lowest number of suppliers, 70 suppliers in network co-ordinator 1 and 30 in network co-ordinator 2, compared with the preferred and approved categories, but those suppliers that achieve the strategic partner status should be well integrated with the buying organisation and its established supply chain due to their strategic importance.

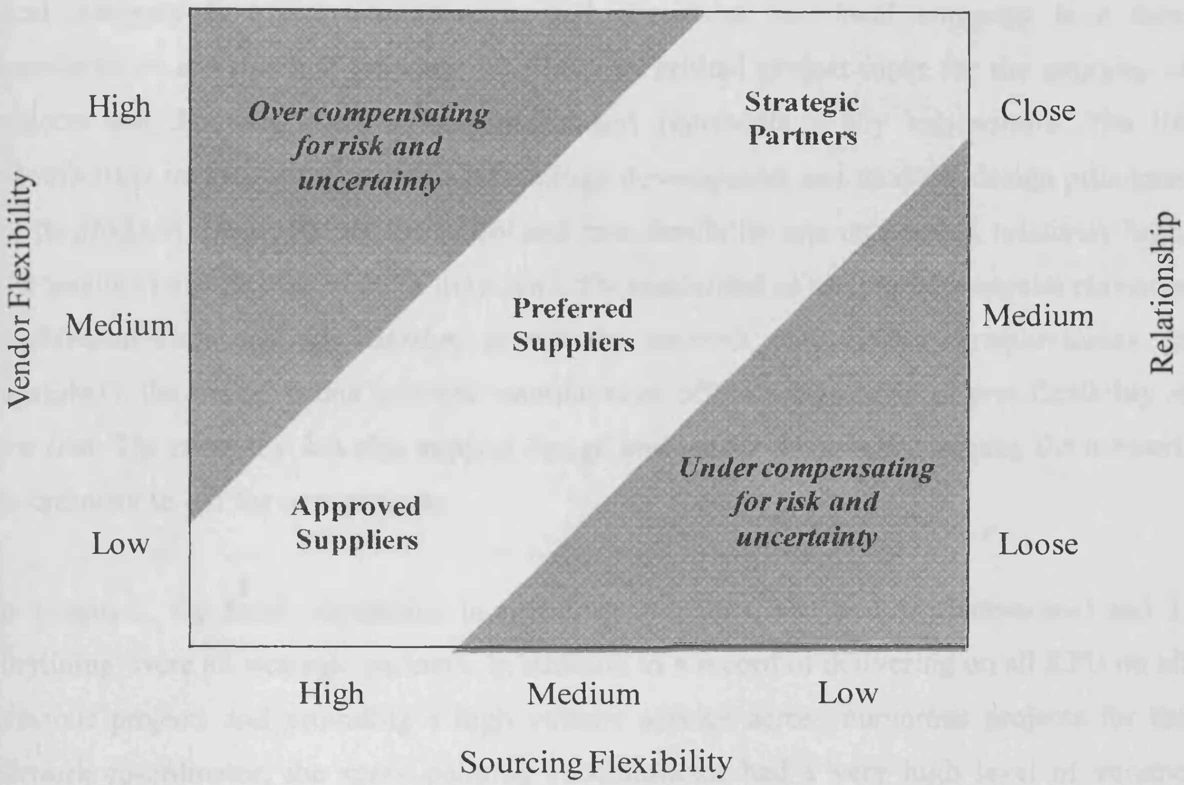


Figure 7.5: Interaction between supply chain flexibility antecedents

In this category there is a high level of vendor flexibility, a level of sourcing flexibility and close relationships. The aim is to build close relationships by investing in the development of the supplier in order to achieve high levels of supply chain flexibility through vendor flexibility, as opposed to sourcing flexibility. The network co-ordinator will need to look carefully at both the external and internal flexibilities of these strategic partners with the aim of maximising vendor flexibility in relevant areas of interest. A supplier may be promoted to this category as a result of its overall flexibility levels or due to specific flexibility qualities, such as high levels of new product flexibility. Sourcing flexibility will be lower as a result of a 'lock-in' effect, whereby any change in supplier would result in the loss of investment in the supplier, so transaction costs associated with changing supplier will be higher.

Table 7.1 shows the different suppliers in the study and the purchasing category in which they are grouped. It shows that in system 1 the focal companies in pipelines A, where the focal company is a lift manufacturer, and G, where the focal company is a door manufacturer, are strategic partners. The lift is a critical project input for the majority of projects that the case company completes and represents a key expenditure. The lift manufacturer invests heavily in new technology development and modular design principles for its products. New product flexibility and mix flexibility are, as a result, relatively high. The product range is also wide as they can offer residential as well as commercial elevators of different sizes and specification to suit the network co-ordinator's requirements. In pipeline G, the timber frame systems manufacturer offers a high level of mix flexibility at low cost. The company can also support design and tender documents, helping the network co-ordinator to bid for new projects.

In system 2, the focal companies in pipelines J (paint), K (modular bathrooms) and L (drylining) were all strategic partners. In addition to a record of delivering on all KPIs on all previous projects and providing a high volume service across numerous projects for the network co-ordinator, the spray painting subcontractor had a very high level of volume flexibility. As previously noted, through a pool of flexible skilled labour and site managers the workforce could be enlarged dramatically to suit the needs of a project. The focal company in pipeline K was responsible for all high specification commercial toilets and bathrooms for the network co-ordinator. There was regular demand for the product from project to project, and the company delivered excellent results on all KPIs. The company offered a high level of mix flexibility and new product flexibility at a low cost achieved through modular offsite manufacturing techniques. The drylining and safety systems subcontractor in case L, offered a high level of mix flexibility in terms of drylining systems coupled with a flexible metal workshop. It was also able to offer specialist expertise in safety systems and has established supply chain relationships with relevant suppliers.

Overall, suppliers in this group tended to offer complex work packages and assume responsibility for a defined area of a project. High levels of new product flexibility, mix flexibility and volume flexibility appear to be important external flexibilities for this group of suppliers. These capabilities also help suppliers contribute to bid and tender support for network co-ordinators.

Supplier	System	Product	Supplier Category
A	1	Elevators	Strategic Partner
B	1	Windows	Preferred
C	1	Pre-cast concrete	Preferred
D	1	Roof Trusses	Preferred
E	1	Metalwork	Approved
F	1	Brickwork	Approved
G	1	Timber frame systems	Strategic Partner
H	1	Doors	Preferred
I	1	Timber	Approved
J	2	Paint	Strategic Partner
K	2	Modular bathrooms	Strategic Partner
L	2	Drylining	Strategic Partner

Table 7.1: Summary of pipeline suppliers and the purchasing categories

Strategic suppliers in system 2 were developed through formal training courses run by network co-ordinator 2. This included a passport programme, which included a number of training modules that are targeted at managers within key suppliers. The training programmes ensure that management within suppliers are conversant with leading best practice in project management, processes and procedures. A 'passport' is achieved by attending a series of these training modules. Suppliers keep track of their progress with a stamp card showing the different courses which have been completed. These suppliers are given early visibility of projects in the pipeline, more consistent workflow and become more involved in tender development. They would be used for the core activities that are consistently demanded across different construction projects, such as mechanical and electrical work packages. Unique or less common requirements for different projects might then be procured from approved or preferred suppliers. The whole supply chain is reconfigured from the three different tiers according to the needs of each project.

7.4.2 Preferred Suppliers

In the preferred supplier category the range of suppliers is higher than the strategic partner category, 180 in the case of network co-ordinator 1 and 90 in network co-ordinator 2, but processes will not be integrated to the same degree as the previous category of supplier. The approach in this category is to balance a moderate amount of vendor flexibility with a moderate level of sourcing flexibility. The network co-ordinator may only wish to look at the external flexibilities offered by such vendors, but if a particular supplier is moving towards a position whereby it may be considered as a strategic partner the network co-ordinator may also wish to take an interest in internal flexibilities. Many practical details will have already been completed, such as health and safety records checked and financial and key contact data stored in a database, so the transaction costs associated with contacting and contracting a supplier will be reduced. Switching costs are lower than the strategic partner category as there will be less of the 'lock-in' effect. This should accelerate integration into a project supply chain.

In system 1, the focal companies in pipelines B, C, D and H were preferred suppliers. In pipeline B, there was a consistent demand for widows across projects and they were purchased at a moderate volume. However, there were many different suppliers of windows, and, while the company has performed reasonably well in terms of KPIs, the record was not yet sufficient for promotion to the strategic partner category. There is a moderate amount of demand for pre cast concrete (C). Not all projects managed by network co-ordinator 1 used pre-cast concrete as a construction method, so the supplier was not required for every project. In the case of H, the demand for doors is regular, but the product is relatively standard, and there are a lot of other suppliers offering similar products. Overall, suppliers in this category are used relatively frequently for different projects that require their products and services. However, vendor flexibility levels, and other key determinants of supplier selection, are not sufficient to warrant a promotion to strategic partner.

7.4.3 Approved Suppliers

Approved suppliers represent the biggest group of suppliers used by both network co-ordinators: 500 suppliers in the case of network co-ordinator 1 and 180 for network co-ordinator 2. The approach here is to develop a high level of sourcing flexibility. There is little lock-in effect and a premium is placed on the ability of the network co-ordinator to reconfigure the supply chain with little penalty in time or cost. In contrast to strategic partners, the network co-ordinator may only wish to look at the external flexibilities offered by such vendors, and the vendor flexibility level requirements may be low. Relationships are loose with little investment by the network co-ordinator in developing the supplier or integrating processes. Sourcing through this category of supplier has much in common with arms length spot trading where a network co-ordinator may put a package of work out to tender among a number of approved suppliers.

The focal companies in cases E, F and I fall under this category. Bricks and timber are both standard products with many potential suppliers in the marketplace. In most cases these are 'supply' only contracts with little value adding services other than the supply of standard materials. While demand is consistent for both of these product groups, and delivery flexibility is relatively high as products are purchased from stock, there is a very low supply risk and the complexity of the offering is low. The metalwork supplier in pipeline E had no in-house design capability and, therefore, could offer very little new product flexibility. Volume flexibility is also limited as the company is a small – medium enterprise (SME) with a very small site. Overall, suppliers in this group tended towards standard goods on a supply only basis. Delivery flexibility appeared to be the external flexibility that network co-ordinators most require from this category.

7.4.4 The integration of supply chain flexibility and purchasing

Figure 7.6 summarises the integration of supply chain flexibility and purchasing dimensions. It shows the original criteria of the purchasing model, the supply chain flexibility implications with reference to vendor and sourcing flexibility and the supplier development requirements in the three different categories.

An important conclusion to be drawn from this table is that there are different ways of achieving flexibility. High levels of vendor flexibility can be developed with strategic partners and high levels of sourcing flexibility can be developed by switching between approved or preferred suppliers. The intermediate category, preferred suppliers, offers moderate levels of both flexibility types. As a result, the network co-ordinator should focus on developing the internal flexibility of strategic partners, while minimising transaction costs in switching between approved suppliers. Furthermore, a network co-ordinator can maintain a suitable level of supply chain flexibility by maintaining a pool of suppliers in each category.

Supplier Group	Criteria	Supply Chain Flexibility Implications	Developing Supplier Flexibilities
Strategic Partners	•Regular demand for product •Critical product •High proportion of spend •Excellent performance record •High supply risk •High level of supplier development	• High vendor flexibility • Low sourcing flexibility	•External and internal flexibilities
Preferred Suppliers	•Moderate demand for product •Critical or non critical •Moderate proportion of spend •Moderate supply risk •Moderate level of supplier development	• Moderate vendor flexibility • Moderate sourcing flexibility	•External and internal if supplier will 'progress'
Approved Suppliers	•Low demand for product •Critical or non critical •Low proportion of spend •Low supply risk •Low level of supplier development	• Low vendor flexibility • High sourcing flexibility	•External flexibilities only

Figure 7.6: Integration of supply chain flexibility and the purchasing model

7.5 THE ROLE OF SUPPLY CHAIN FLEXIBILITY IN MITIGATING PROJECT UNCERTAINTIES

Table 7.2 shows the generic uncertainties for the projects in the study categorized according to the supply chain uncertainty source. Vendor and sourcing flexibilities have been mapped onto this table of uncertainties to indicate the role they can play in mitigating or responding to different uncertainties. Those that are not marked are areas where supply chain flexibility would not be effective in mitigating the uncertainty and are outside the ability of the supply network to respond.

Two of the demand uncertainties can be managed by supply chain flexibility. Late changes by the client can be mitigated through vendor flexibility. On a sustainable housing project in System 1 the client changed the specification of the grain-effect coating of the doors during the construction phase of the project. The door supplier was able to respond to the new requirements, source the required materials and scale up production to meet the new requirements to ensure there were no delays on the project. Technological uncertainty can also be supported by supply chain flexibility. For example, an elevator manufacturer in System 1 invested much into research and development and has the expertise to support network main contractors in bidding for projects that require complex technological solutions in their area. Alternatively, the main contractor may search through preferred or approved contractors for specialists in the required area.

A number of process uncertainties can also be mitigated. Uncertainty over the availability of equipment can be mitigated by allowing a supplier to take ownership of the delivery of a 'package' of work. A manufacturer of pre-cast concrete in System 1 managed the design, manufacture, delivery and installation (including plant and equipment) of pre-cast concrete. Similarly, uncertainty over labour can be supported by vendors with high levels of labour flexibility. On a commercial tower project visited in System 2, a painting contractor regularly recruited extra gangs of labour to meet the progress requirements of the project. If the speed of construction and volatility of workflow is unpredictable, this can also be mitigated with high levels of vendor flexibility.

Supply chain flexibility can be used to mitigate five of the control uncertainties. Sourcing flexibility will contribute to the competency of the team as the network co-ordinator with high sourcing flexibility has the ability to reconfigure the supply chain to get the right team for a particular project. This includes a mixture of strategic partners, preferred suppliers and approved suppliers, and also includes the ability of the network co-ordinator to encourage shared objectives and effective contractual arrangements. A high level of vendor flexibility will help to respond to any changes in project milestones. High levels of both vendor and sourcing flexibility will help to overcome activities that are not accounted for in the planning-process.

Uncertainty	Supply Chain Uncertainty Type	Vendor	Sourcing
Timely/correct information from clients	Control	0	0
Timely/correct information from consultants	Control	0	0
Fragmented decision making	Control	0	0
Permissions from regulators	Control	0	0
Effectiveness of contractual arrangements	Control	0	1
Shared objectives	Control	0	1
Competency of project team	Control	1	1
Achieving project milestones	Control	1	1
Things not accounted for in planning	Control	1	1
Client non payment	Demand	0	0
Appropriate or effective design for scheme	Demand	0	0
Late changes in specification	Demand	1	1
Drawing approvals	Demand	0	0
New technology or technique	Demand	1	1
Scheme viability long term	Demand	0	0
Design too rigid to accommodate change	Demand	0	0
Construction market conditions	External	1	1
Weather	External	1	0
Geology/site characteristics	External	1	0
Final cost	Process	1	1
Desired equipment unavailable	Process	1	1
Accuracy of project plan	Process	1	1
Quality/Excessive snagging	Process	0	0
Labour resources	Process	1	1
Competency of site management	Process	0	0
Deliveries unable to access site	Process	0	0
Delivery bottlenecks	Process	0	0
Amount of storage space available	Process	0	0
Amount of work space available	Process	0	0
Site impact on local community	Process	0	0
Speed of construction	Process	1	0
Volatility of workflow	Process	1	0
Safety hazards	Process	0	0
Security	Process	0	0
Damages	Process	0	0
Timely and correct information from suppliers	Supply	1	0
Early or late deliveries	Supply	1	1
Subcontractor bankruptcy	Supply	1	1
Bad performance from suppliers	Supply	0	1
Capacity of subcontractors	Supply	1	1
Consistency of suppliers	Supply	1	1
Responsiveness of suppliers	Supply	1	1
Total		20	18

Table 7.2: Uncertainties that can be mitigated with supply chain flexibility

Supply chain flexibility can also play a role in responding to external uncertainties. In times of changing market conditions the ability to reconfigure suppliers may help to support movement into new markets. The network co-ordinator in System 2 decided to begin bidding for nuclear power projects to counterbalance the downturn in the commercial office sector and used the skills of the suppliers to support this. Suppliers with high level of vendor flexibility allow projects to react to unforeseen geological features and excessive bad weather.

Vendor and sourcing flexibility play a comprehensive role in responding to all 7 supply uncertainties. Suppliers with high levels of delivery flexibility are able to respond to due date changes quickly, hence reducing uncertainty related to early or late deliveries. A high level of sourcing flexibility mitigates the risks associated with subcontractor bankruptcy. In a commercial tower project in system 2 a façade supplier went bankrupt during the construction phase and the network co-ordinator quickly integrated a new supplier into the supply chain. The uncertainty relating to the capacity of subcontractors and responsiveness of suppliers is characteristic of low vendor flexibility. This can be addressed by developing suppliers or by leveraging the capacity of a number of different suppliers. Communications flexibility of suppliers and the network co-ordinator facilitates timely and correct information exchange. The network co-ordinator in system 2 had a web based information management system which suppliers could log into to get up-to-date information for different aspects of projects they are involved with.

7.6 DISCUSSION AND STATEMENT OF CONTIBUTION

The literature relating to flexibility has recognized the need to adopt a supply chain perspective, rather than the restricted scope of manufacturing flexibility (Duclos et al., 2003; Pujawan, 2004; Sanchez and Perez, 2005; Swafford et al., 2006; Vickery et al., 1999). However, the supply chain flexibility field is still at an early stage, and consensus regarding definitions, scope, meaning and application has not yet been achieved. This thesis has helped to address this by providing a classification of the supply chain literature (see table

2.11 in the literature review) and a conceptual model for supply chain flexibility (see figure 7.1 at the start of this chapter). It also offers an empirical investigation of supply chain flexibility in the construction industry in this chapter, something that is lacking in the literature on supply chain flexibility.

Furthermore, in a sector dominated by projects, often varying in frequency, scope and scale, strategic partnerships need to be considered vis-à-vis flexibility requirements. The role of supply chain flexibility has not been addressed in purchasing. A purchasing model for network co-ordinators in ETO construction supply chains was developed, which investigates three different relational categories between network co-ordinators and suppliers.

The importance and contribution of this chapter is

While the importance of flexibility has been acknowledged, much of the research relating to flexibility has addressed non ETO manufacturing. There is a recognition that the scope needs to be widened to consider the flexibility of the whole supply chain, but the literature in this area is at a very early stage of development. Flexibility has also not been investigated empirically in the ETO construction sector. This chapter develops a model of supply chain flexibility, identifying the sources of flexibility as 'vendor' and 'sourcing' flexibility. It also provides, an empirical investigation in the two ETO construction supply chains, showing that flexibility may be achieved by integrating these two sources of flexibility with a three-tiered purchasing model. The chapter supports the claim that flexibility is an important strategic capability, and increases researchers and practitioners understanding of flexibility.

7.7 CONCLUSION

This chapter has specifically addressed the research question 'How can flexibility be rationalised in ETO construction supply chains'? Supply chain flexibility has been rationalised for the ETO sector, proposing the antecedents of vendor flexibility and sourcing flexibility. A purchasing model was developed using case study data collected from two network co-ordinators in the construction industry and purchasing criteria outlined in the purchasing literature. Three categories of supplier were investigated: approved suppliers, preferred suppliers and strategic partners. Vendor and sourcing flexibility were integrated with the purchasing model, developing the argument that different categories of supplier have different implications for supply chain flexibility. The final section explored the role of supply chain flexibility in mitigating uncertainties experienced in five different construction projects. Vendor and sourcing flexibility were mapped onto the generic uncertainty profile developed in chapter 5 to ascertain which uncertainties could be mitigated by supply chain flexibility.

Network co-ordinators operating in project environments can achieve supply chain flexibility by balancing vendor flexibility and sourcing flexibility through three different categories of supplier: strategic partners, preferred suppliers and approved suppliers. Strategic partners are associated with high levels of vendor flexibility and approved suppliers are associated with high levels of sourcing flexibility. Preferred suppliers are an intermediate category offering moderate levels of vendor and sourcing flexibility. A network co-ordinator can maintain a healthy balance of supply chain flexibility by maintaining a pool of suppliers in each category.

The findings show that supply chain flexibility can mitigate 23 of the project uncertainties identified in ETO projects. These include uncertainties from all of the different sources of supply chain uncertainty. More specifically, it suggests that five control uncertainties, two demand uncertainties, three external uncertainties, six process uncertainties and seven supply uncertainties can be alleviated with different facets of supply chain flexibility. This chapter makes a case for supply chain flexibility to be integrated with mainstream purchasing models.

SUMMARY OF CHAPTER 8 AIMS

1. **Present the findings from the evaluation interviews**
   - The findings from the evaluation interviews for each research question have been discussed in turn
2. **Evaluate the findings for each research question using findings from the evaluation interviews**
   - The findings from the evaluation interviews for each research question have been integrated with the findings from the case study phase
3. **Present a framework for achieving flexibility in supply chains**
   - A four step framework has been presented including identify supply chain structure, identify sources of uncertainty, optimise pipelines and configure network with required flexibility
4. **Evaluate the strengths, weaknesses, opportunities and threats related to the research**
   - A SWOT analysis has been presented and discussed
5. **Discuss the contribution of the evaluation interviews in to validity concerns**
   - The contribution of the evaluation to the overall validity of the thesis has been discussed. In particular, the contribution of the evaluation interviews to generalisability claims have been addressed.

CHAPTER 8

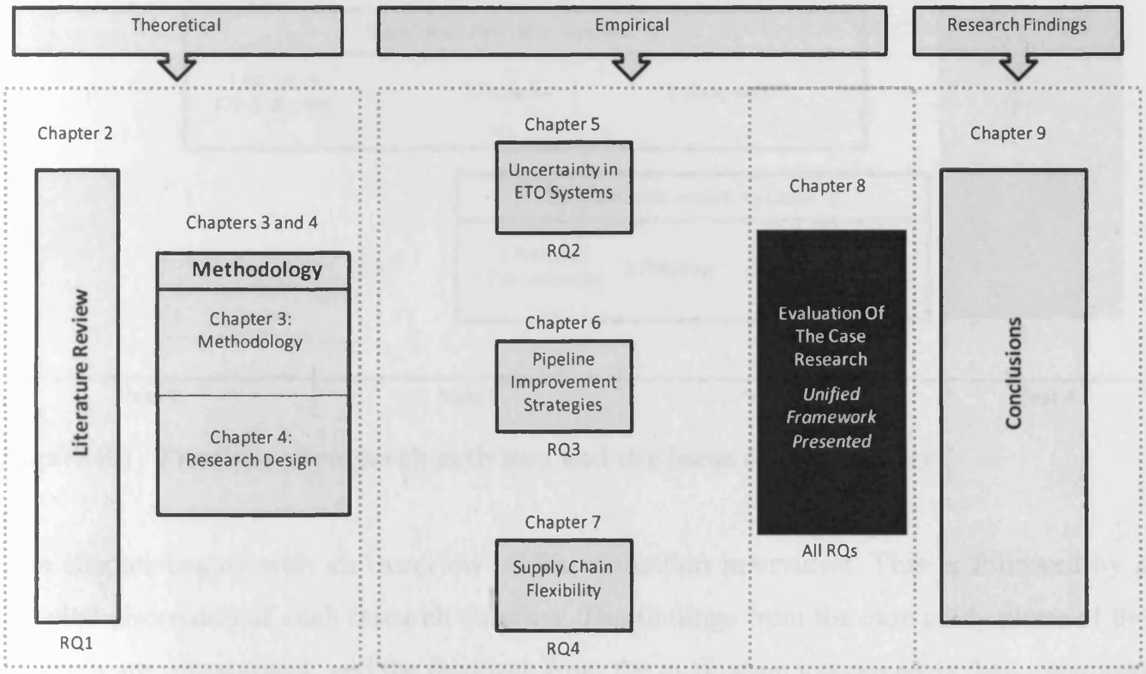
EVALUATION OF THE CASE RESEARCH

CHAPTER 8 AIMS

1. **Present the findings from the evaluation interviews**
2. **Evaluate the findings for each research question using findings from the evaluation interviews**
3. **Present a framework for achieving flexibility in supply chains**
4. **Evaluate the strengths, weaknesses, opportunities and threats related to the research**
5. **Discuss the contribution of the evaluation interviews in to validity concerns**

RESEARCH QUESTION ADDRESSED

All research questions are addressed in this chapter



8. INTRODUCTION

This chapter provides an assessment of the results and findings from the case study phase of the research. The case study phase of the research has provided rich and detailed data for each of the research questions. However, although the cases were selected purposely, with depth and breadth achieved through embedded units of analysis, the extent of the applicability of these findings across ETO construction sectors is unclear from the case findings alone. Through 6 evaluation interviews conducted with interviewees outside of the two case systems, this chapter provides some indication of the generalisability of the findings of the study to other settings. It also enriches the answers to the research questions generated from the case study phase. This phase of the thesis is indicated by the shaded area in figure 8.1., and it shows that the evaluation interviews were conducted in the final year of the research.

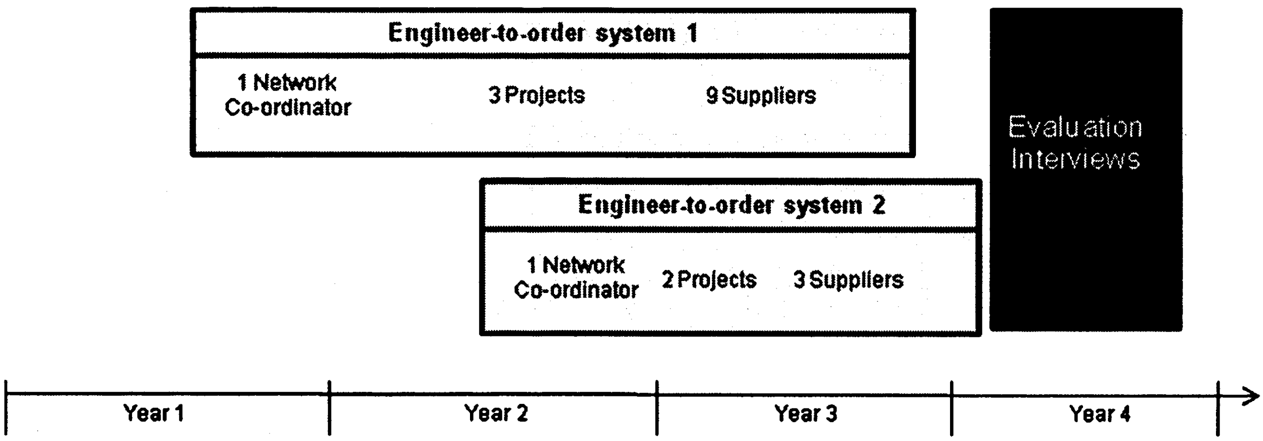


Figure 8.1: Timeline of research activities and the focus of this chapter

The chapter begins with an overview of the evaluation interviews. This is followed by a detailed discussion of each research question. The findings from the case study phase of the research are summarised, and the feedback from the evaluation interviews is then integrated with these findings. Using the feedback from the evaluation interviews a SWOT (strengths, weaknesses, opportunities and threats) analysis is conducted. The chapter finishes with an appraisal of the validity of the research and its generalisability. Conclusions are then drawn. It is important to note that the focus of this chapter is to assess the findings from a practitioner perspective. The academic contributions are discussed more fully in the final chapter.

8.1 METHOD OVERVIEW

As described in the methodology chapter, evaluation interviews were conducted with a purposely selected range of interviewees from different organisation types and different ETO sectors. The author presented the findings of the case study phase of the research, which was structured using the 4 different research questions. Each interview lasted around 2 hours. The aims of this activity were as follows:

1. Assess the accuracy, completeness, value, fairness and perceived validity of the findings by external review;
2. Evaluate the extent to which the findings can be generalised to different ETO sectors;
3. Evaluate the strengths, weaknesses, opportunities and threats associated with the research;
4. Enhance and enrich findings with evaluative empirical data;
5. Identify avenues for further research.

Six evaluation interviews were conducted. The types of organisations, the position of the interviewee and the sector associated with each interviewee are shown in table 8.1. In this chapter the findings from the evaluation interviews are discussed alongside findings from the case study phase of the research.

Interview	Type of Organisation	Position of Interviewee	Sector
1	Architect	Architect	Residential and Commercial Projects
2	3rd Party Logistics Provider	Business Unit Manager	Range of sectors including building materials
3	Non departmental public body	Lead Technologist	Range of construction and manufacturing sectors
4	Civil engineering contractor	Operations Manager	Civil Engineering
5	Government department	Procurement Manager	Range of public sector construction projects
6	Government department	Contracts Manager	Public sector civil engineering projects

Table 8.1: Overview of evaluation interviews

8.2 INTEGRATING THE CASE STUDY FINDINGS WITH THE EVALUATION INTERVIEW FINDINGS

The remainder of the chapter will address the individual research questions posed in this thesis.

8.2.1 Research Question 1: How does construction fit within a taxonomy of supply chain structures?

By undertaking a structured literature review of the ETO supply chain, and by grounding the empirical construction focused phases of the research in the ETO literature, this thesis has argued that construction is a particular form of ETO supply chain. The evaluation interviews looked to develop this argument by presenting the taxonomy of supply chain structures to interviewees and probing the likeness of the ETO supply chain with different structures.

During the literature review, a taxonomy of six supply chain structures, including the engineer-to-order (ETO), buy-to-order (BTO), make-to-order (MTO), assemble-to-order (ATO), make-to-stock (MTS) and ship-to-stock (STS) supply chain was proposed. A review of the literature relating to supply chain structures led to the development of different attributes for the ETO supply chain. The decoupling point is based at the design stage and the sources of supply are identified to order. The organisation carries no stocks and a new design is produced for each order. Production methods include project and job shop where forecasting accuracy is very low. Levels of customisation are higher than in all other structures and volume and time to market are lower than all other structures.

The structured literature review founds that the ETO supply chain operates in a project environment and that each product is different to the last. Production dimensions of the supply chain are completely customised and the decoupling point is located at the design stage. However, existing designs maybe modified to order or completely new designs are developed to order. There may also be sector specific differences. For example, each construction project has to be completed on a new site, whereas shipbuilding may take place at a fixed location.

In this thesis, the ETO supply chain has also been rationalised as a system, consisting of network co-ordinators, who assume responsibility for configuring the network of suppliers, subcontractors and interdependent organizations. These organisations work together to deliver the specific projects that the network co-ordinator organisation is currently involved with. A range of supplier pipelines are required for order fulfilment, this includes the activities that take place between generating an order and the receipt of that order into the project.

A summary of the feedback regarding this research question by each of the interviewees is shown in table 8.2. Interviewees were all able to relate their working environment to supply chain structures and the ETO supply chain, with the decoupling point located at the design stage. However, as pointed out succinctly by interviewees 2 and 3, it is likely that there are decoupling points within the design phase of the ETO supply chain, and that varying levels of standardisation in the design stage are employed across different ETO sectors. This agrees with the structured literature review, which concluded that there are varying levels of design re-use across ETO sectors. All interviewees recognised the units of analysis and their interaction as a valid description of the ETO system. Interviewees 5 and 6 pointed out though that there are many more stakeholders that impact on the system in public construction projects and that there is a blurry line between the client and the network co-ordinator in public procurement. Interviewees 4 highlights that there are there are subtle differences between different ETO construction sectors. In civil engineering projects the site itself is likely to be a lot larger, increasing the risk of groundwork uncertainties.

Interview	How does construction fit within a taxonomy of supply chain structures?
1	*No Comment*
2	• Many construction sectors fit into the ETO category, but there may be different degrees of standardisation in terms of the designs. • The system conceptualisation does not address the role of a logistics company in the ETO supply chain.
3	• The supply chain structures diagram is an accurate and useful framework for thinking about different supply chains. • Within the ETO sector there are varying levels of design standardisation. Perhaps there are a range of decoupling points within the design stage.
4	• Civil engineering projects are arguably more bespoke and customised than house-building or commercial projects. • The design aspect of the ETO project places considerable uncertainty and complexity into the system.
5	• Sometimes the role of the client and the network co-ordinator can become blurred in ETO supply chains.
6	• Public procurement projects have a great many stakeholders that have to be considered outside of the defined 'system'.

Table 8.2: Summary of feedback from the evaluation interviews for research question 1

8.2.2 Research Question 2: How can the sources of project uncertainty in ETO construction supply chains be identified and categorised?

In chapter 5, a five stage method was presented, which included the following steps: identify uncertainties, create uncertainty profiles, categorize uncertainties according to supply chain uncertainty source and originator, model interactions between uncertainties and use positioning matrix to identify severity. The empirical investigation reported demonstrates how the framework may be applied to a group of projects. The method may be applied at the level of an individual project, or for selected groups of projects either within or between different companies.

For the group of construction projects that the method was applied to, 42 uncertainties were identified comprising of 9 control uncertainties, 7 demand, 3 external, 16 process and 7 supply uncertainties. A cause and effect diagram was developed to explore further the causes and relationships between different uncertainties. This identifies the causes of control, demand, process and supply uncertainties. The causes of control uncertainties were found to be ineffective contractual arrangements, poor supply chain management and poor planning and project management. The root causes of process uncertainties were found to be inadequate resources, poor site logistics and poor site management. The causes of supply uncertainty were found to be supplier financial failure, inadequate supplier capabilities, poor visibility of site progress, orders not placed in time and late changes to orders. Finally, demand uncertainties were found to be caused by inadequate or inappropriate designs, delays approving designs, financial problems and market changes. The uncertainties were then plotted on a graph to show the likelihood of a negative impact occurring and the potential impact.

The supply chain uncertainty model used to categorise the uncertainties received positive comments from all interviewees. It was perceived as useful as it broadens the debate about risk and uncertainty to the wider supply chain. A summary of the feedback from each of the interviewees regarding this research question by is shown in table 8.3. All interviewees confirmed that the 42 uncertainties identified were recognisable to those working in the ETO construction sector. None of these uncertainties were disputed, but further uncertainties were identified. Interviewee 5 argued that in public procurement projects there is the additional uncertainty of a change of government, a change in budget or change in the focus of policy. A further root cause was also highlighted as 'disruption to the project team'.

Interviewees 1 and 3 both suggested that while contractual issues are mentioned in the 42 uncertainties, and in the cause and effect analysis conducted, the contract type had profound implications for the management and allocation of risk and uncertainty, and is not addressed from the client perspective. Interviewee 5 proposed 'project related insurance' as a solution to risk and uncertainty allocation. This technique uses a common insurance policy for a project, forcing different members of a supply chain to share risk and uncertainty while still having contractual relationships.

Interview	How can the sources of project uncertainty in ETO construction supply chains be identified and categorised?
1	• The supply chain uncertainty circle is useful as it forces you to think about the broader sources of risk and uncertainty. • The supply chain uncertainty model misses the importance of contract type. This will affect the way in which risk and uncertainty is managed and allocated.
2	• The ETO sector needs to be forced to think more carefully about risk, uncertainty and reward. It is not currently adequately pricing risk into operations.
3	• Does not address the way that different procurement routes influence uncertainty, such as design and build vs public private partnerships. • The impact of uncertainties is not limited to time and cost. It can also impact on quality and environmental performance. Companies are increasingly being asked to show their quality and sustainability credentials.
4	*No Comment*
5	• Public sector procurement has a different demand uncertainty profile. A change in government, a policy change or budget implications all affect operations.
6	• Excessive bad weather is a particular problem in civil engineering projects as much of the work is undertaken across large areas of land involving digging up earth.

Table 8.3: Summary of feedback from the evaluation interviews for research question 2

While the uncertainties were undisputed, the relative importance of different uncertainties was disputed. For example, in civil engineering the weather was identified as one of the highest impact with the highest likelihood of occurring. Interviewee 6 proposed that the weather had a high impact on civil engineering projects as the construction work is spread over large areas of land. This makes it unfeasible to take the measures to reduce the impact of weather that are possible in, for example, housebuilding. Interviewee 3 pointed out that, in addition to cost and time, uncertainty can also be viewed in terms of negative impact on quality and sustainability. Uncertainties, therefore, have different levels of importance in different ETO construction sectors, and they also have a greater impact than merely on time and cost.

As previously mentioned, the five stage method represents the main contribution from this element of the research. The method has been investigated during the case phase of the research using a group of five projects. This shows how the method may be applied, but it is worth noting that the results for each application may differ.

8.2.3 Research Question 3: How can organisations improve pipelines in ETO construction supply chains?

The literature review highlighted the importance of understanding and improving the pipeline. The first step in improving supplier pipelines is to gain a greater understanding of pipeline activities. The generic activities in the ETO construction pipeline can be defined as: an initial enquiry, design and approval of a product, procurement of the relevant materials, manufacture and assembly, transport to the site and then final integration of the product with the site. Of these activities, the design stage is the most variable and time consuming activity in the pipeline with an average variability of 70 days for the pipelines involved in this study. The results also indicate that as the lead time increases it gets more variable. The scope of responsibility differs between focal companies. Some companies will take on responsibility for all pipeline activities and include a full work package; others take on only selected responsibilities.

The problems that companies experience in the pipeline were investigated in the pipeline survey. Ten generic pipeline problems were identified which are as follows and are listed with the frequency that the problem occurred in the pipeline survey shown in brackets after each source: design changes/incorrect specification (6), establishing site readiness (5), labour shortages (4), information exchange (4), supply risks (3), integration of related trades on site (3), access issues (2), excessive product variation (2), payment and chains of custody (2), and tender uncertainty (2). The sources of advantages for the focal companies in pipelines were analysed. Ten sources of competitive advantage were identified which are as follows and are listed with the frequency that the source occurred in the pipeline survey shown in brackets after each source: Specialist expertise (6), supply chain integration (6), information technology systems (3), logistics capabilities (3), labour (3), management systems and processes (3), new product and process innovation (3), manufacturing excellence (2), modularity (2) and a flexible organisational structure (2).

A summary of the feedback by each of the interviewees regarding this research question is shown in table 8.4. The response from interviewee 1, suggesting that buying organisations often underestimate the length of lead times, and do not adequately understand the potential problems, underlines the importance of the descriptive elements of the pipeline survey. Interviewee 4 underlined that variability in the pipeline can introduce many of the problems identified.

Interviewee 2 reinforced the need to work with suppliers closely from the beginning of the design process, if full value is to be realised. Interviewee 6 arranged 'project bank accounts' that suppliers can draw from to alleviate problems associated with late payments filtering down the supply chain. A further point, made by interviewee 3, is that the solutions to problems in the pipeline may depend on the contract type or relationship type with the network co-ordinator. No further problems or sources of competitive advantage were suggested.

Interview	How can organisations improve pipelines in ETO construction supply chains?
1	• Buyers often underestimate the length of lead times and do not see the potential problems that can occur. Network co-ordinators must think a lot further in advance about starting pipeline activities.
2	• Suppliers must be included at the start of the design process. This would reduce uncertainty and should improve design for manufacture.
3	• The solutions to the pipeline problems identified may depend upon the contract type or the relationship with the customer.
4	• Variability in the pipeline is a big problem for buying organisations. Consistency is more important than a short lead time.
5	*No Comment*
6	• Project bank accounts have been pioneered in the public sector. This reduces the problems associated with non payment and chains of custody. Using this system suppliers do not have to wait for payments from customers' customers to trickle through to them.

Table 8.4: Summary of feedback from evaluation interviews for research question 3

8.2.4 Research Question 4: How can flexibility be rationalised in ETO construction supply chains?

In the literature review, and in chapter 7, supply chain flexibility was rationalised by proposing the antecedents of vendor flexibility and sourcing flexibility. A three tiered purchasing model was developed using case study data collected from the two network co-ordinators and purchasing criteria outlined in the purchasing literature. Three categories of supplier were proposed including approved suppliers, preferred suppliers and strategic partners. Vendor and sourcing flexibility were then integrated with the purchasing model, developing the argument that different categories of supplier have different implications for supply chain flexibility. Strategic partners are associated with high levels of vendor flexibility and approved suppliers are associated with higher levels of sourcing flexibility. Preferred suppliers are an intermediate category offering moderate levels of both vendor and sourcing flexibility. A network co-ordinator can maintain a healthy balance of supply chain flexibility by maintaining a pool of suppliers in each category.

Chapter 7 then investigated the role of supply chain flexibility in mitigating uncertainties experienced in five different construction projects. Vendor and sourcing flexibility were mapped onto the generic uncertainty profile developed in chapter 5 to ascertain which uncertainties could be mitigated by supply chain flexibility. The findings show that supply chain flexibility can help to mitigate 23 of the project uncertainties identified. These include uncertainties from all of the different sources of supply chain uncertainty. More specifically, it suggests 5 control uncertainties, 2 demand uncertainties, 3 external uncertainties, 6 process uncertainties and 7 supply uncertainties which can be alleviated using either vendor or sourcing flexibility.

A summary of the feedback regarding this research question by each of the interviewees is shown in table 8.5. All interviewees apart from interview 1 were aware of, and had engaged with, purchasing models based on different criteria. Many companies used a similar model, either formally or informally. However, none had formally considered the role of flexibility in supplier selection. Two further criteria for the purchasing model were suggested including the power relationships (interviewee 3) and the complexity of a product or service package (interviewee 1).

However, interviewee 4 suggested that the recession at the time of writing may have undermined the strategic partnership approach. The recession has made it difficult to offer strategic partners a consistent workload. Suppliers from the lower tiers, or unknown suppliers, are aggressively bidding for work. Consequently, more new and approved suppliers are forcing their way into the supply chain, potentially undermining strategic partnerships.

Interview	How can flexibility be rationalised in ETO construction supply chains?
1	• The criteria and thinking for purchasing model is logically sound. • It is essential if you find a supplier that does a good job to stick with them and face uncertainty together. The more complex a package of work is, the more need there is for a strategic partner.
2	• These purchasing models can also apply to the procurement of logistics services. The focus with approved suppliers is control; the focus with strategic partners is development.
3	• Choice of vendor or sourcing flexibility may depend on power relationships in the supply chain.
4	• We use similar principles to the purchasing model – although they are not formally articulated. • We are finding that the strategic partnering model has been undermined by the recession. • How much flexibility is required?
5	• Public procurement has limited scope for structuring the supply base as per the model. Suppliers for public civil engineering projects must meet government qualification criteria. Contracts above a certain value must also be put out to competitive tender – so strategic partners cannot automatically be awarded work.
6	• Flexibility is essential. However, you have got to be able to change in the right way, and get the right capabilities. • How much does it cost to become flexible?

Table 8.5: Summary of feedback from the evaluation interviews for research question four

A potential limitation of the purchasing model is its lack of applicability to public procurement projects. As noted in table 8.5, suppliers for public civil engineering projects must meet government qualification criteria. In addition, contracts above a certain value must automatically be put out to competitive tender, eliminating the scope to award strategic partners work. The purchasing model must, therefore, be reconsidered for application in the public sector. This is an avenue for further research.

All interviewees accepted the definitions of the antecedents of supply chain flexibility, vendor and sourcing flexibility, and found it a useful way to 'operationalise' and consider supply chain flexibility. The distinction between internal and external flexibilities was a useful and meaningful distinction for industry. Interviewee 4 raised the issue of measuring sourcing flexibility: 'How do you measure the ability of a company to switch between suppliers?' A potential route for further research would be the development of measuring systems for the different elements of sourcing flexibility. Based on the dimensions of sourcing flexibility identified in the literature review, a measurement system could be developed to assess the ability to reconfigure the network, the ability to adapt the network to market requirements, the ability to increase supplier responsiveness and to assess the integration of the supply chain. A related point is highlighted by interviewee 5: 'How do you assess how flexible a supplier is?" This relates to the measurement of vendor flexibility. While the framework for external flexibilities was perceived as a useful framework to consider the flexibility of suppliers, a formal tool for assessing suppliers' capabilities may improve commercial utility.

The finding that supply chain flexibility can mitigate 23 of the uncertainties produced mixed responses from interviewees. Interviewee 3 suggested that uncertainty related to damages would require either vendor or sourcing flexibility to respond. This was not proposed in the original classification. Interviewee 4 suggested that all uncertainties related to information exchange cannot be solved by the ability to be flexible alone. The ability to switch between modes of communication effectively would not, by itself, help to mitigate these uncertainties. It would also need proactive team working. However, as argued in the literature review section of this thesis, flexibility involves range and response. The latter includes the ability to proactively respond. All other interviewees confirmed that supply chain flexibility could be used to mitigate the 23 uncertainties.

A final point is raised by interviewee 5, who suggested that good market awareness is an essential enabler for supply chain flexibility. This is the ability to monitor the market and looking forward, to predict what capabilities will be required in the future. The company must then take action to ensure that it has these capabilities.

Interviewee four raised the question 'How much flexibility is required?' While this is an important question, it is beyond the scope of this thesis, and has been addressed analytically by Tang and Tomlin (2008) who, using analytical models, showed that the benefits of flexibility can actually be achieved with low levels of flexibility. Interviewee 6 raised the question 'How much does flexibility cost?' This research has identified the types of flexibility required, but has not addressed the potential cost of flexibility. A cost – benefit analysis for different flexibility types and capabilities could be considered as an avenue for further research that would make the findings to this research question more commercially applicable.

8.2.5 Integrating the findings of the case study and research and the evaluation interviews

Table 8.6 provides a synthesis of the findings of the case study phase of the research and the evaluation interviews for each research question. The findings from the evaluation interviews confirm, enrich and give an indication of the generalisability of the case findings. They add much to the validity of the research. A discussion of the ways in which validity claims have been supported by the evaluation interviews can be found at the end of the chapter.

RQ	Findings from Case Studies	Findings from Evaluation Interviews
RQ1	• The literature review established the ETO supply chain as one of six supply chain structures • The ETO supply chain operates in a project environment where production dimensions of the supply chain are completely customised, and the decoupling point is located at the design stage. • Case 'systems' were rationalised to show how suppliers, projects and network co-ordinators interact in an ETO construction supply chain.	• Interviewees from the construction sector were all able to relate their working environment to the ETO supply chain • Decoupling points exist within the design phase of the ETO construction supply chain. The amount of standardization in the design process differs between construction sectors.
RQ2	• Applying a five-stage method to 5 construction project led to the identification of 42 uncertainties, comprising 9 control uncertainties, 7 demand, 3 external, 16 process and 7 supply uncertainties. • A cause and effect analysis identified the causes of uncertainty • The relative importance of those uncertainties was mapped using impact and likelihood metrics	• The supply chain uncertainty circle is a useful and meaningful way of analysing uncertainty. • The uncertainties identified are stable across ETO Construction environments, but the relative importance of these uncertainties may differ between sectors. • In addition to time and cost, uncertainty might also impact on quality and sustainability performance dimensions.
RQ3	• The pipeline includes an initial enquiry, design and approval, procurement, manufacture and assembly, transport to the site and then final site integration. • The design stage is the most variable and time consuming activity. • As the lead time increases it gets more variable • 10 generic pipeline problems and 10 sources of competitive advantage were identified.	• The descriptive elements of the pipeline survey were confirmed. • Two further solutions were suggested: early involvements of suppliers in the design process and project bank accounts. • Solutions to problems in the pipeline may depend on the contract type and relationship type with the network co-ordinator.
RQ4	• Supply chain flexibility can be rationalised using antecedents of vendor flexibility and sourcing flexibility. • A 3 tiered purchasing model was developed including approved suppliers, preferred suppliers and strategic partners. • Vendor and sourcing flexibility were integrated with the purchasing model. • The findings show that supply chain flexibility can help to mitigate 23 of the project uncertainties identified.	• Definitions of vendor and sourcing are recognised as useful for 'operationalising' supply chain flexibility. • In addition to the 23 uncertainties, supply chain flexibility can also help to mitigate uncertainty related to damages. • 3 tiered purchasing model is unsuitable for application in the public sector. • Unanswered questions include 'how much flexibility is required' and 'how much does flexibility cost?'

Table 8.6: Integration of findings for all research questions

8.3 A FRAMEWORK FOR ACHIEVING APPROPRIATE FLEXIBILITIES TO MITIGATE THE UNCERTAINTIES IN ETO CONSTRUCTION SUPPLY CHAINS

A number of interviewees had queries regarding implementation issues. This raises an important point relating to action research and implementing change in organisations. The action research cycle has been identified as observe, reflect, plan and act (Elliot, 1991). The planning phase will include a form of diagnosis and an analysis of observations. The plan may include recommendations about what needs to change supported by tools methods or frameworks. The last stage, act, represents the implementation phase, where a change is initiated in the organisation (Coughlan and Coghlan, 2009). This research primarily addresses observe, reflect and plan phases, offering definitions, diagnostics and recommendations for change rather than implementing change. The assumption made is that industrialists know their organisation best, and are in a position to take the findings and use them effectively in their organisations.

To support this planning phase, a framework, or route map for industry, is developed for achieving flexibility. This describes the pragmatic steps required to achieve flexibility in the supply chain. The 'act' phase is beyond the scope of this thesis, and would also move the thesis into a different methodological orientation. Potential change programmes are suggested in the future research activities in the conclusions. This section pulls together the thesis to develop a framework for achieving the flexibilities to mitigate uncertainty in different supply chains. The framework is shown in figure 8.2. It shows four steps for achieving supply chain flexibility, and acts as a route map for companies to follow. It aims to explain the pragmatic steps required to implement the findings of this thesis. The research questions have been integrated with these four steps to show how the framework relates to the different elements within the thesis. The four steps are now discussed in turn.

8.3.1 Step 1 – Identify the supply chain structure

The need to match supply chain strategy with structure has been outlined in the literature review. Six different supply chain structures were identified. Accordingly, the first step is the framework is the identification of the decoupling point. This can be achieved, primarily, by considering the form of strategic stock in the supply chain and the extent to which different supply chain activities are customised or standardised for each order. This thesis has addressed the ETO structure within the specific setting of the construction industry.

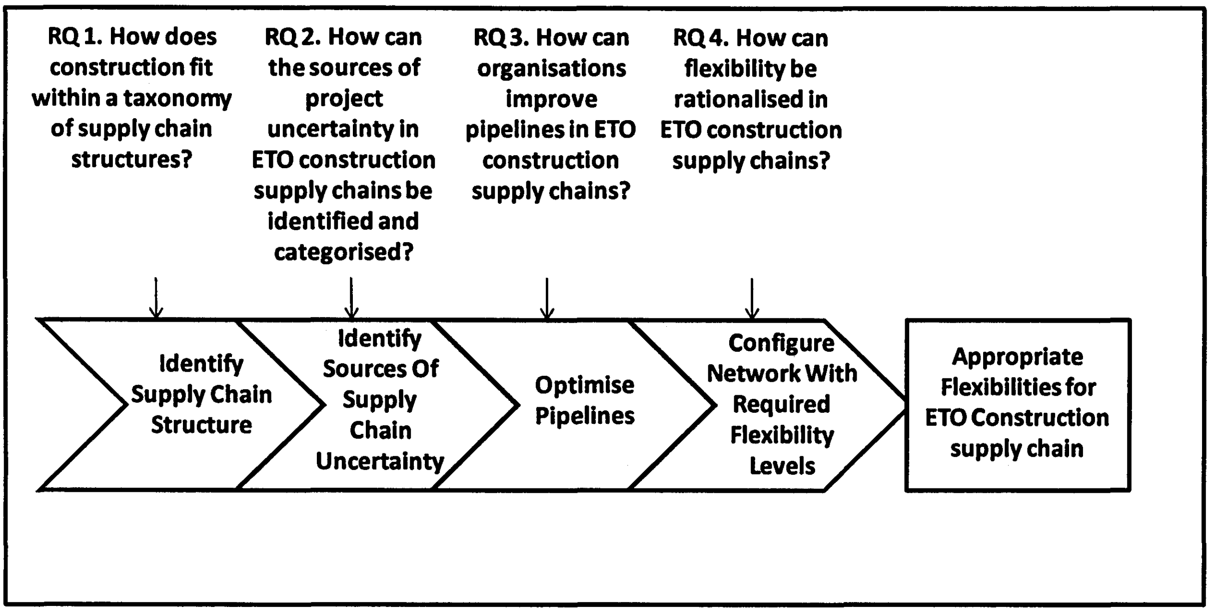


Figure 8.2: A framework for achieving flexibility in ETO supply chains

8.3.2 Step 2 – Identify the sources of supply chain uncertainty

The next step is to identify the uncertainties in the supply chain. This can be approached by categorising uncertainties according to the different sources of uncertainty articulated in the supply chain uncertainty circle: supply, demand, process, control and external uncertainties. The root causes of these different uncertainties can then be explored through cause and effect analysis. The relative importance of these uncertainties can be analysed by considering the likelihood that a negative effect will come to fruition and the impact that an uncertainty could have on time, cost, quality and sustainability performance measures.

8.3.3 Step 3 - Optimise pipelines

Network co-ordinators must fully understand the activities in the pipeline and the lead time implications. This will involve understanding and documenting techniques, such as the input-output diagrams and process flow charting, simplification, by removing problems and improving information and material flows throughout the pipeline. The final stage is re-engineering to reduce problems in the pipelines. This thesis has produced four recommendations for pipeline improvement strategies:

1. Reduce uncertainty by addressing the problems in the pipeline;
2. Strive for shorter and more consistent lead times;
3. Consider the sources of competitive advantage in pipeline improvement strategies;
4. Work together to improve pipelines.

8.3.4 Step 4 – Configure the network with required flexibility

This thesis has argued that the supplier network can be structured using a 3 tiered purchasing model, which is integrated with supply chain flexibility considerations. The first action for an organisation, therefore, is to organise the existing supply base according to these tiers. This would involve examining the criteria for the different tiers, and identifying which suppliers are, or should be, approved, preferred and strategic partners.

Once this has been achieved, the development of supply chain flexibility can be addressed. It should also be noted that flexibility would be one of the criteria considered for placing suppliers in the different supplier tiers. Network co-ordinators can then begin to develop strategic partners by offering formal training in flexibility in the required areas and capabilities. The next stage would be to develop sourcing flexibility capabilities for approved and preferred suppliers. The classification developed in the literature review suggests that the key abilities here are:

- Ability to reconfigure the supply chain;
- Ability to adapt to market requirements;
- Ability to increase supplier responsiveness;
- Ability to integrate the supply chain.

The final stage is to establish a performance management system to address the promotion and demotion through performance monitoring. The experience of the network co-ordinator from system 1 suggests that KPIs and a dedicated supply chain manager are essential for this last stage.

8.4 EVALUATION

This final section seeks to give a closing evaluation of the findings before conclusions are drawn.

8.4.1 Strengths, weaknesses, opportunities and threats

Based on the feedback from the evaluation interviews, figure 8.3 shows the perceived strengths, weaknesses, opportunities and threats (SWOT) of the research. This is intended to summarise the strengths and weaknesses of the research from a practitioner perspective.

Strengths

The first perceived strength of the research is the objectivity and holistic approach adopted in the research. Many of the interviewees felt that problems, risks and uncertainties are usually analysed from a very specific or narrow perspective, serving particular needs. This research was perceived as holistic, including the wider supply chain in the analysis of uncertainty. The research was also perceived to have integrity by interviewees, with clear relationships between data and findings. The result is an accurate and unbiased investigation of the problems facing the ETO construction sector. The definitions, models, methods and frameworks were also felt to be useful for driving innovation and change. In particular, many of the interviewees enjoyed stepping out of the day-to-day fire fighting from within their organisations and discussing strategy in the context of the evaluation presentation.

Weaknesses

The evaluation interviews identified three omissions from the research. The first omission is that the system conceptualisation does not include transport and logistics activities. Whereas these are identified as part of the pipeline, they are not shown in the conceptualisation of the ETO system. As mentioned in the discussion of the research question 2 above, the contractual arrangements are not addressed in this research. Finally, the research does not offer a current state assessment of sourcing flexibility.

STRENGTHS	WEAKNESSES
•Research approach is holistic and objective, whilst also being very close to industry •An accurate and insightful representation of uncertainties in ETO projects •Integrity of research process •Framework and flexibility definitions are useful for driving innovation and change in industry	•Does not adequately address contractual arrangements as a barrier or enabler of flexibility •The role of a logistics provider is not addressed •Does not address the assessment of current flexibility capabilities
OPPORTUNITIES	**THREATS**

•Pipeline improvement workshops
•Potential for further development of commercial tools and techniques related to:
  •Uncertainty identification and analysis
  •flexibility capability assessment and matching
  •Organising the supply base
•Potential for application in different sectors
	•Cultural and organsational barriers to change
	•Incurring too much cost by overcompensating for flexibility
	•No clear overall management and direction of flexibility at the system level.

Figure 8.3: SWOT analysis

Opportunities

Interviewee 7 suggested that the findings from chapter 5 relating to pipelines would be useful in supplier training days, whereby suppliers and the network co-ordinator come together to analyse, discuss and improve pipelines.

Most of the other opportunities identified by practitioners in the evaluation interviews relate to tool development. In the areas of uncertainty, identification and analysis, and opportunities for developing and formalising the method undertaken for collecting and synthesizing the uncertainties would be welcomed, as well as integrating these techniques with formal risk management frameworks. The models for organising the supply base were felt to be a useful decision support tool for practitioners and could initiate change programmes for re-engineering business processes. A complete tool kit would allow organisations to assess their current capabilities in terms of flexibilities, and also allow them to identify the required flexibilities for the uncertainties in their supply chains.

Finally, there are opportunities for application of these models, tools and techniques outside of the ETO sector. As described in the literature review, many organisations, even those outside of the ETO sector, are trying to make their supply chains more responsive, and are trying to offer more choice to customers. The findings from this thesis, therefore, may offer insight for such organisations to achieve more responsive and customised supply chains.

Threats

The first threat identified was the cultural and organisational barriers to change. In particular, the problem of initiating customer focused change in non customer facing activities was highlighted. The issues of 'who pays for flexibility?' and 'how much does it cost?' were also identified as potential threats. A cost – benefit analysis for different flexibility types and capabilities can be considered as an avenue for further research which would make the findings to this research question more commercially applicable. A further threat highlighted was the danger that there is no clear overall management of flexibility in the supply chain.

8.4.2 Validity and Generalizability

The subject of validity in research was introduced in the methodology chapter. In addition to the validity concerns addressed in the research design of the case research, the evaluation interviews presented in this chapter have helped to address overall validity concerns in the study. Firstly, the evaluation interviews have improved the claim to portray an accurate relationship between variables in the various models and classifications developed. The models exposed to outside scrutiny are as follows:

- The uncertainty circle and the 42 uncertainties;
- The cause and effect of different uncertainties;
- The causal modelling for pipeline problems;
- The causal modelling for the sources of competitive advantage in the pipeline;
- The conceptual model for supply chain flexibility;
- The purchasing model for ETO construction supply chains;
- The classification of flexibility types for ETO construction supply chains;
- The findings of the flexibility mapping technique.

While measures were taken throughout the case research process to ensure the accuracy of these models and classifications, they have also been subjected to outside scrutiny from a range of stakeholders from outside of the case systems, but within the focal sectors that the research seeks to generalise. As described above, in some cases, the models, findings and classifications were enriched by the evaluation interview.

By integrating the findings of the two phases of the research, the following can be concluded:

- Construction is a particular form of ETO supply chain, but the amount of design standardization differs across construction sectors;
- The uncertainties identified, and the cause and effect relationships between these uncertainties, are consistent across different construction sectors, but the relative importance of these uncertainties is not consistent;
- The generic activities in the pipeline for construction suppliers can be defined as: an initial enquiry, design and approval of a product, procurement of the relevant materials, manufacture and assembly, transport to the site and then final integration of the product with the site;
- Ten different pipeline problems for construction suppliers can be identified which are recognised across different construction sectors;
- Ten sources of competitive advantage can be identified in the pipeline; these are recognised across different construction sectors;
- Supply chain flexibility can be rationalised using antecedents of sourcing and vendor flexibility. An ETO network can be configured to cope with uncertainty using a 3 tiered purchasing model which is integrated with these antecedents to achieve supply chain flexibility. A network co-ordinator operating in the ETO construction sector can best cope with uncertainty by maintaining a pool of suppliers in each category;
- Supply chain flexibility, defined as consisting of vendor and sourcing flexibility, can help to mitigate at least 23 of the uncertainties identified in the construction projects.

The evaluation interviews have also considerably bolstered the claim of this research to external validity, also known as generalisability. The difficulties of statistical generalisation from case research have been described in the methodology chapter. The feedback from the evaluation interviews gives a good indication of the generalisability of the findings to different construction sectors. A summary of the distinct areas of generalisability has been articulated. However, it must still be acknowledged that while the case selection criteria, and the sample of 6 interviewees, was designed to offer the most effective investigation of the target population, it is still a small sample. Larger scale testing, such as a questionnaire, would be required to make more accurate statements regarding the external validity of the findings.

8.5 DISCUSSION AND STATEMENT OF CONTRIBUTION

While this chapter has addressed all the research questions, and synthesised findings from previous chapters, it provides direct answers to 2 elements of the thesis that have not yet been articulated. Firstly it allows a statement of importance and contribution relating to research question one (How does construction fit within a taxonomy of supply chain structures?) to be formulated. This is as follows:

ETO and construction disciplines have evolved in isolation. This thesis integrates the thinking within the disciplines and places construction within a taxonomy of supply chain structures. In the literature review a taxonomy of six supply chain structures was proposed, which included ETO, BTO, MTO, ATO, MTS and STS supply chain. Definitions of each supply chain type were developed, and the construction supply chain literature was integrated with the ETO body of knowledge via a structured literature review. Bringing together the structured literature review, the case study phase of the research, and by analysing feedback from the evaluation interview, this thesis argues that construction is a particular form of ETO supply chain. However, it indicates that design standardization varies between different construction sectors.

Recall that the primary aim of the thesis was to **develop a framework for achieving appropriate flexibilities to mitigate the uncertainties in ETO construction supply chains.** This chapter has integrated different elements of the thesis to develop a four stage framework to satisfy this primary aim. In relation to the primary aim, the following can be articulated:

Bodies of knowledge on uncertainty, flexibility, pipelines and collaboration have largely evolved independently, and have not been integrated for the specific needs of the ETO construction sector. Based on the different elements of the research, a four stage framework for achieving appropriate flexibilities to mitigate the uncertainties in ETO construction supply chains has been presented to satisfy the primary aim of the research and fill this research gap.

8.6 CONCLUSIONS

This chapter has summarised the findings from the case study phase for each of the four research questions. These findings have then been discussed with reference to empirical data collected from 6 evaluation interviews. A framework for achieving flexibility in an ETO construction supply chain was then presented consisting of four steps: identify supply chain structure, identify supply chain uncertainties, optimise pipelines and configure the network with required flexibility. Each step relates to the research questions in the thesis. This can act as a route map for practitioners to implements the findings of this research. A SWOT analysis of the research has also been presented based on the empirical data collected in the evaluation interviews. The final section addresses the role of the evaluation interviews in the claims to validity for the study. The evaluation interviews are considered to improve the claims to internal, construct and external validity. In particular, this chapter is important as it strengthens the potential to generalise the findings to different ETO construction environments.

SUMMARY OF CHAPTER 8 AIMS

1. **Present the findings from the evaluation interviews**
   - The findings from the evaluation interviews for each research question have been discussed in turn
2. **Evaluate the findings for each research question using findings from the evaluation interviews**
   - The findings from the evaluation interviews for each research question have been integrated with the findings from the case study phase
3. **Present a framework for achieving flexibility in supply chains**
   - A four step framework has been presented including identify supply chain structure, identify sources of uncertainty, optimise pipelines and configure network with required flexibility
4. **Evaluate the strengths, weaknesses, opportunities and threats related to the research**
   - A SWOT analysis has been presented and discussed
5. **Discuss the contribution of the evaluation interviews in to validity concerns**
   - The contribution of the evaluation to the overall validity of the thesis has been discussed. In particular, the contribution of the evaluation interviews to generalisability claims have been addressed.

CHAPTER 9

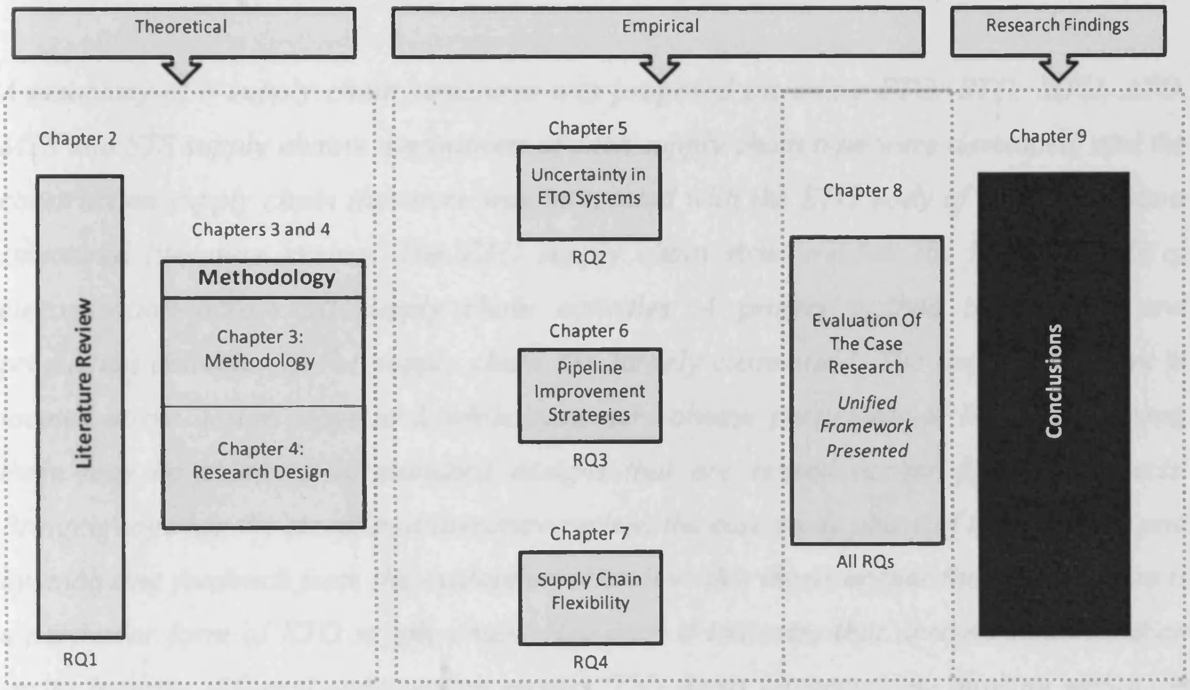
CONCLUSIONS

SUMMARY OF CHAPTER 9 AIMS

1. **Articulate concise answers to each of the research questions**
2. **Summarise the research findings in relation to the primary aim of the thesis**
3. **Identify the academic contributions**
4. **Identify the implications for practitioners**
5. **Identify the limitations and areas for further research**

RESEARCH QUESTION ADDRESSED

All research questions are addressed in this chapter



9. INTRODUCTION

This final chapter summarises the research findings. A concise answer to each of the four research questions is articulated. A short discussion of the findings from the research in relation to the primary aim set out at the start of the thesis is offered, along with a clear statement of the extent to which findings can be generalised. The original contributions to the literature are highlighted and the implications for practitioners are summarised. Finally, the limitations and avenues for further research are identified.

9.1 ANSWERS TO RESEARCH QUESTIONS

9.1.1 Research question 1: How does construction fit within a taxonomy of supply chain structures?

A taxonomy of 6 supply chain structures was proposed including ETO, BTO, MTO, ATO, MTS and STS supply chains. Definitions of each supply chain type were developed, and the construction supply chain literature was integrated with the ETO body of knowledge via a structured literature review. The ETO supply chain structure has the highest levels of customisation across all supply chain activities. A project method is required, and production activities in the supply chain are largely customised. The decoupling point is located at the design stage and, while customers always participate in the design phase, there may be elements of standard designs that are reused across different projects. Bringing together the structured literature review, the case study phase of the research, and by analysing feedback from the evaluation interview, this thesis argues that construction is a particular form of ETO supply chain. However, it indicates that design standardization varies between different construction sectors. This thesis integrates the thinking within the disciplines and places construction within a taxonomy of supply chain structures.

9.1.2 Research question 2: **How can the sources of project uncertainty in ETO construction supply chains be identified and categorised?**

A five-stage method was developed, including identify uncertainties, create uncertainty profiles, categorize uncertainties according to supply chain uncertainty source and originator, model interactions between uncertainties and use positioning matrix to identify severity. The method was applied to a group of 5 construction projects managed by two different network co-ordinators. Using the supply chain uncertainty circle as a framework, 42 uncertainties have been identified via the case research phase, and a further 4 were identified in the evaluation interviews. The sources include those from the demand side, those from the supply side, those from the process and those from the control system. These sources all have different root causes, which can be identified by cause and effect analysis. The evaluation interviews indicate that the uncertainties identified, and the cause and effect relationships between these uncertainties, are consistent across ETO construction sectors, but the relative importance of these uncertainties differs. In addition to time and cost, uncertainty may also impact on quality and sustainability performance dimensions.

9.1.3 Research question 3: How can organisations improve pipelines in ETO construction supply chains?

The generic activities in construction supply pipelines can be defined as: an initial enquiry, design and approval of a product, procurement of the relevant materials, manufacture and assembly, transport to the site and then final integration of the product with the site. Of these activities, the design stage is the most variable and time consuming activity in the pipeline. As lead times get longer they tend to become more variable. Ten different pipeline problems can be identified, and the evaluation interviews indicate that these are recognised across different ETO construction sectors. There is less agreement on the solutions offered. The solutions to the problems in the pipeline may depend on the contract type and relationship type with the network co-ordinator. Ten sources of competitive advantage can be identified, and the evaluation interviews indicate that these are recognised across different ETO construction sectors To improve supplier pipelines in ETO systems organisations should consider addressing the 10 problems in the pipeline, strive for short *and consistent lead-times, develop sources of competitive advantage in the pipeline and, finally, work together to achieve these goals.*

9.1.4 Research question 4: How can flexibility be rationalised in ETO construction supply chains?

Supply chain flexibility can be achieved in an ETO construction supply chain by using a 3 tiered purchasing model which is integrated with antecedents of supply chain flexibility. Three categories of supplier, including approved suppliers, preferred suppliers and strategic partners, are proposed, each with different vendor and sourcing flexibility implications. Strategic partners are associated with high levels of vendor flexibility and approved suppliers are associated with higher levels of sourcing flexibility. Preferred suppliers are an intermediate category offering moderate levels of both vendor and sourcing flexibility. A network co-ordinator can best cope with uncertainty by maintaining a pool of suppliers in each category. The case study phase suggests that supply chain flexibility can mitigate 23 of the uncertainties identified. A further uncertainty that could be mitigated was identified at the evaluation interview stage. Market awareness may be an important enabler for establishing how much flexibility is required.

9.3 GENERALIZABILITY

While this thesis is grounded in the ETO literature, it focuses on the construction sector. The case study phase and the evaluation interviews are all conducted within the construction industry. Therefore this thesis only focuses on the potential to generalize to the ETO construction sector, rather than the wider ETO sector.

By integrating the findings of the case phase and the evaluation interviews, the following can be concluded regarding the generalizability of findings to the ETO construction sector.

- The ETO construction supply chain can be rationalised as a system, consisting of network co-ordinators, who assume responsibility for configuring the network of suppliers, subcontractors and interdependent organizations that work together to deliver projects, the specific projects that the network co-ordinator organisation is currently involved with and a network of supplier pipelines.

- The 42 uncertainties identified, and the cause and effect relationships between these uncertainties, are consistent across different construction sectors, but the relative importance of these uncertainties is not consistent.
- The generic activities in the pipeline for construction suppliers can be defined as: an initial enquiry, design and approval of a product, procurement of the relevant materials, manufacture and assembly, transport to the site and then final integration of the product with the site.
- Ten different pipeline problems for construction suppliers can be identified which are recognised across different construction sectors.
- Ten sources of competitive advantage can be identified in the pipeline; these are recognised across different construction sectors.
- Supply chain flexibility can be rationalised using antecedents of sourcing and vendor flexibility. An ETO construction network can be configured to cope with uncertainty using a 3 tiered purchasing model which is integrated with these antecedents to achieve supply chain flexibility. A network co-ordinator operating in the ETO construction sector can best cope with uncertainty by maintaining a pool of suppliers in each category.
- Supply chain flexibility, defined as consisting of vendor and sourcing flexibility, can help to mitigate at least 23 of the uncertainties identified in the construction projects.

9.3 A SUMMARY OF RESEARCH FINDINGS IN RELATION TO THE PRIMARY AIM OF THE THESIS

Recall that the primary aim of this thesis is **to develop a framework for achieving appropriate flexibilities to mitigate the uncertainties in ETO supply chains.**

Chapter 2 argues that the ETO supply chain is one of six supply chain structures and the particular attributes of the ETO supply chain structure are a good 'conceptual fit' with the characteristics of agility. Agility is a strategic approach to supply chain management based on responsiveness and flexibility. A structured literature review was undertaken to provide a more precise classification of the characteristics of the ETO supply chain, and a classification of the different strategic approaches to improving ETO supply chains. The structured literature review also highlights the methodological landscape of the area and an overview of the sectors that are associated with the ETO supply chain. The final part of the literature review establishes a relationship between uncertainty and flexibility, suggesting that flexibility is an effective response to uncertainty. Finally, a conceptual model for supply chain flexibility was developed, which is an expansion of the principles of manufacturing flexibility to the wider supply chain. Vendor and sourcing flexibility were proposed as the 'antecedents' of supply chain flexibility. The primary aim was broken down into 4 research questions.

Chapter 3 provides a context to the research design of the thesis. The philosophical stances of positivism, critical realism and constructivism are discussed. The overall research stance of critical realism is identified and multiple case study research is identified as the primary empirical phase of the research. A review of the strengths and weaknesses of a range of research methods that are pertinent to the thesis was presented.

Chapter 4 expands chapter 3, explaining how the research methods are applied in the study and linking these with the research questions. Three units of analysis are specified in an ETO 'system'. These are first network co-ordinators, who assume responsibility for configuring the network of suppliers, subcontractors and interdependent organizations that work together to deliver projects, second, the specific projects that the network co-ordinator organisation is currently involved with and, third, a network of supplier pipelines. The multiple case studies consist of 2 network co-ordinators, 5 projects and 12 supplier pipelines. This is followed by seven evaluation interviews. Validity concerns and controls were addressed at the end of the chapter.

A relationship between uncertainty and flexibility was established in the literature review. In order to understand the flexibility requirements of ETO supply chains, the uncertainties experienced in ETO construction supply chains must be identified. **Chapter 5** presented a five-stage method to identify and categorize uncertainties, which was applied to 5 construction projects. In dong this, the supply chain uncertainty circle was adopted as a framework to classify the uncertainties, and a root causes of these uncertainties was conducted to model the interactions. In total, forty two uncertainties were identified in the case study phase of the research.

If flexibility and responsiveness is to be achieved in ETO supply chains, effective pipelines must be developed. **Chapter 6** investigates the pipeline activities in the case studies. Generic pipeline activities are identified, lead times are analysed, and problems, solutions and sources of competitive advantage are investigated. **Chapter 7** investigates how supply chain flexibility can be achieved. A 3 tiered purchasing model was developed and the antecedents of vendor and sourcing flexibility were integrated with this model. The chapter concludes that 23 of the 42 uncertainties identified can be mitigated through supply chain flexibility.

Chapter 8 integrates the findings from the case study phase of the research with the findings of 6 evaluation interviews. This chapter is important as it provides an indication of the elements of the research that can be generalised to other ETO construction environments. A framework for achieving the appropriate flexibilities in supply chains is developed in chapter 8. This framework brings together all elements of the research, and satisfies the primary aim of the research. It is reprinted below for emphasis, in figure 9.1, but this version integrates the findings for each of the research questions.

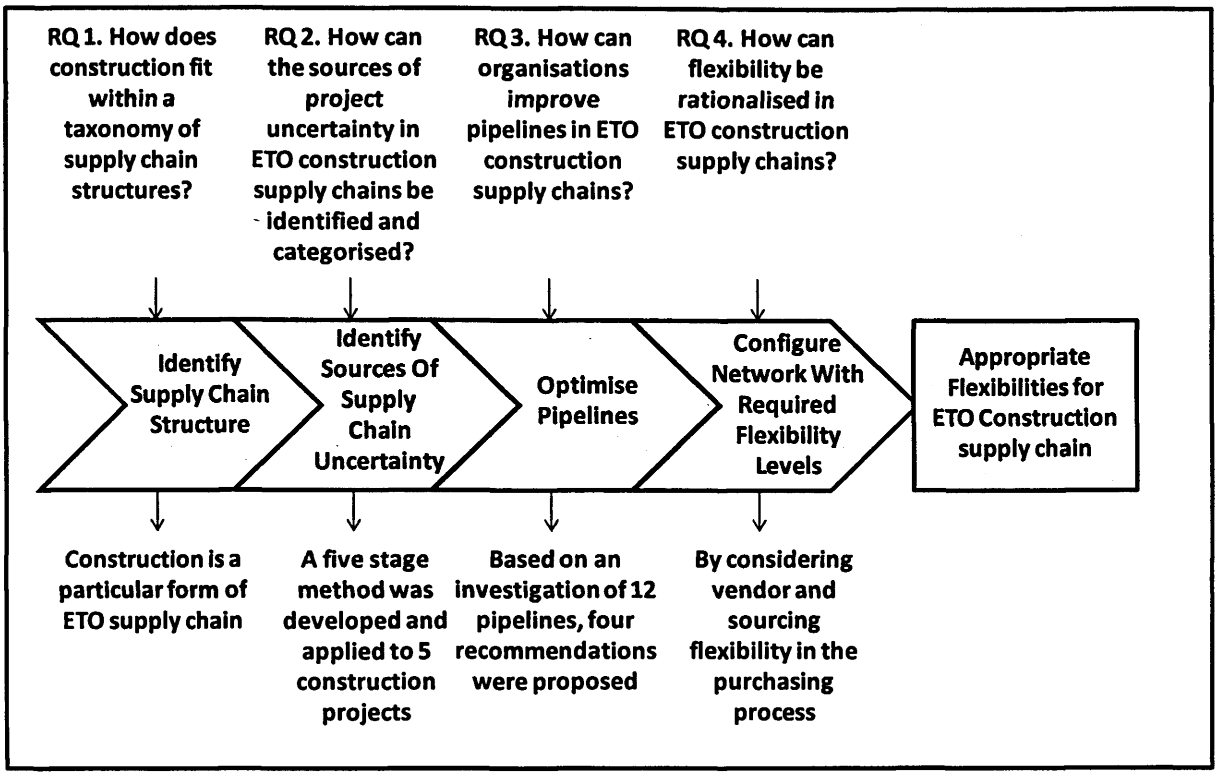


Figure 9.1: A framework for achieving flexibility in supply chains with answers to research questions

9.4 ACADEMIC CONTRIBUTIONS

The research adds to the overall body of literature through a number of contributions. A summary of these contributions, in relation to each of the research questions and the conclusions, can be found in table 9.1. These contributions will be discussed in relation to four types of knowledge creation in logistics and supply chain research proposed by Arlbjørn and Halldorsson (2002). These four types are as follows:

- *Storytelling and/or quantitative testing of new knowledge*. This category focuses on theory testing with a loose theory base (not based in well established theory).
- *Generating new concepts*. This category focuses on theory development with a loose theory base.
- *Refining the existing knowledge base*. This category focuses on theory testing with a solid theory base (well established theory using well recognised language and concepts).
- *Expanding the knowledge base*. This category focuses on theory development with a solid theory base (Arlbjørn and Halldorsson, 2002).

Research Question	Conclusion	Importance & Contribution
(1) How does construction fit within a taxonomy of supply chain structures?	Construction is a particular form of ETO supply chain	ETO and construction disciplines have evolved in isolation. This thesis integrates the thinking within the disciplines and places construction within a taxonomy of supply chain structures.
(2) How can the sources of project uncertainty in ETO construction supply chains be identified and categorised?	By applying a five stage method to a group of 5 construction projects, 42 uncertainties have been identified via the case research phase, and a further 4 were identified in the evaluation interviews.	The five-stage method brings together a range of techniques for analysing uncertainty. This is the first time these techniques have been integrated into a holistic method, and then applied to a group of projects within the ETO construction sector.
(3) How can organisations improve pipelines in ETO construction supply chains?	To improve supplier pipelines in ETO systems organisations should consider addressing the 10 problems identified in the pipeline, strive for short and consistent lead-times, develop sources of competitive advantage in the pipeline and, finally, work together to achieve these goals.	The relationship between main contractors and subcontractors has not been well researched, and pipeline management research has focused primarily on high volume, stable supply chains. This thesis has addressed this gap with a detailed study of 12 supplier pipelines in the ETO construction sector, and by guidance for improving such pipelines
(4) How can flexibility be rationalised in ETO construction supply chains?	Supply chain flexibility can be rationalised by considering vendor and sourcing flexibility. This can be integrated with a 3 tier purchasing model to achieve flexibility.	Flexibility is an important strategic capability for ETO construction companies, but much of the research in this area has addressed non ETO manufacturing. This thesis expands this to consider flexibility of the whole supply chain in the ETO construction sector. It also provides an empirical investigation of flexibility in the ETO construction sector.
Primary Aim: develop a framework for achieving appropriate flexibilities to mitigate the uncertainties in ETO construction supply chains - UNIFIED OUTPUT		
Bodies of knowledge on uncertainty, flexibility, pipelines and collaboration have largely evolved independently, and have not been integrated for the specific needs of the ETO construction sector. Based on the different elements of the research, a four stage framework for achieving appropriate flexibilities to mitigate the uncertainties in ETO construction supply chains has been presented in this thesis.		

Table 9.1: Summary of conclusions and contributions in relation to each of the research questions and the primary aim

The contributions to knowledge made in the thesis are prioritised according to the importance of the contribution, and the nature of each contribution is categorised according to the four knowledge creation categories outlined above in table 9.2. They are now discussed in turn.

1. Rationalisation and empirical investigation of supply chain flexibility in the ETO construction sector

The supply chain flexibility field is still at an early stage and consensus regarding definitions, scope, meaning and application has not yet been achieved. This thesis has made a contribution by rationalising supply chain flexibility into the antecedents of sourcing and vendor flexibility. By integrating supply chain flexibility with a purchasing model, the study has also provided a useful way to operationalise supply chain flexibility. This makes an additional contribution, as an important dimension that has previously had little consideration for supplier selection has been investigated.

Priority	Contribution	Nature of Contribution
1	Flexibility is an important strategic capability for ETO construction companies, but much of the research in this area has addressed non ETO manufacturing. This thesis expands this to consider flexibility of the whole supply chain in the ETO construction sector. It also provides an empirical investigation of flexibility in the ETO construction sector.	Generating new concepts
2	The five-stage method brings together a range of techniques for analysing uncertainty. This is the first time these techniques have been integrated into a holistic method, and then applied to a group of projects within the ETO construction sector.	Refining the existing knowledge base
3	The relationship between main contractors and subcontractors has not been well researched, and pipeline management research has focused primarily on high volume, stable supply chains. This thesis has addressed this gap with a detailed study of 12 supplier pipelines in the ETO construction sector, and by guidance for improving such pipelines	Expanding the knowledge base
4	Bodies of knowledge on uncertainty, flexibility, pipelines and collaboration have largely evolved independently, and have not been integrated for the specific needs of the ETO construction sector. Based on the different elements of the research, A four stage framework for achieving appropriate flexibilities to mitigate the uncertainties in ETO construction supply chains has been presented in this thesis.	Expanding the knowledge base
5	ETO and construction disciplines have evolved in isolation. This thesis integrates the thinking within the disciplines and places construction within a taxonomy of supply chain structures.	Expanding the knowledge base/ Refining the existing knowledge base

Table 9.2: Major contributions to knowledge

Supply chain flexibility, defined using the antecedents of sourcing and vendor flexibility, has been found in this study to have the potential to mitigate 23 of the 42 uncertainties. Empirical studies to date have not provided an indication of the scope of supply chain flexibility to mitigate uncertainties. Therefore, this study provides an important clarification of the extent to which supply chain flexibility can mitigate uncertainty, helping to establish the role of supply chain flexibility.

The conceptual model of supply chain flexibility fits under the knowledge creation category of generating new knowledge. A new model has been proposed to rationalise supply chain flexibility. This has been investigated through empirical research in the ETO construction sector. This adds to the supply chain flexibility body of knowledge, and the ETO strategy literature.

2. Developing and applying a five-stage method for identifying and categorizing uncertainty in ETO construction supply chains

The literature review highlighted the potential disruptions that uncertainty can lead to within a supply chain. The five-stage method developed in the thesis brings together a range of techniques for identifying and categorizing uncertainty. This is the first time these techniques have been integrated into a holistic method, and then applied to a group of projects within the ETO construction sector. By developing and applying the five-stage method, two specific minor contributions can be highlighted:

- The supply chain uncertainty circle has been successfully applied in a range of sectors, but there are no applications in the ETO construction sector. By applying the supply chain uncertainty circle concept to a novel area this thesis has made the contribution of refining an existing model;
- The model of interactions applied in the five-stage method provides a novel tool for identifying the cause and effect of uncertainties.

3. Identification of pipeline improvement strategies for ETO construction supply chains

An important gap addressed in this thesis is the investigation of pipeline activities between main contactors and their suppliers in construction projects. The majority of the literature in has addressed the client – contractor relationship. Pipeline management has been identified in the literature as crucial for effective supply chain management, but much of the research has been undertaken within stable MTS supply chains. The pipeline survey conducted in this thesis has identified the generic activities in the pipeline, and the lead-time analysis illustrates the time bottlenecks and areas of variability. The problems and sources of competitive advantage in the pipeline have also been identified. This expands the knowledge base by providing an empirical investigation of pipeline management in the particular context of the ETO construction supply chain. The contribution has been recognised by the International Journal of Agile Manufacturing (Gosling et al., 2007a)

4. **A four stage framework that integrates supply chain structure, supply chain uncertainty, pipeline improvement strategies and supply chain flexibility**

The framework proposed in figure 9.1 integrates the concepts investigated in this thesis, and is considered to be the main output of the thesis. It synthesises concepts related to supply chain structures, supply chain uncertainty, pipeline management and supply chain flexibility. This makes the important contribution of consolidating and establishing relationships between fields and concepts. This can be categorised under the knowledge creation type of refining the existing knowledge base.

5. **Placing construction within a taxonomy of supply chain structures**

Most of the literature in supply chain management has addressed repetitive, standardised supply chains. This thesis has focused on the ETO supply chain within the specific setting of the construction industry, where activities are customised for a particular order. ETO and construction disciplines have evolved in isolation. This research integrates the thinking from these disciplines and places construction within a taxonomy of supply chain structures, arguing that it a particular form of ETO supply chain. Positioning construction as a particular form of ETO supply chain helps companies and researchers consider more appropriate strategies. The thesis adds weight to the body of knowledge suggesting that a 'one-size-fits-all' approach to supply chain management is not appropriate. Overall, this thesis also firmly establishes the ETO structure as an important consideration in the family of supply chain structures. In addition, the literature review provides the first structured review of the ETO supply chain to be published (Gosling and Naim, 2009).

9.5 SUMMARY OF IMPLICATIONS FOR INDUSTRY

The implications for industry are fully discussed in chapter 8, so this section will only provide a brief summary. The findings herein will be of interest to practitioners in organisations that have to cope with the complexities and uncertainties inherent in ETO supply chains. It provides a convincing case for the need to develop flexible, agile supply chains in the ETO sector. A framework for mitigating uncertainty is provided, and the thesis offers a structured route to achieving flexibility. The important steps for practitioners to carry out are as follows: identify supply chain structure, identify sources of supply chain uncertainty, optimise pipelines and configure network with required flexibility.

9.6 LIMITATIONS

While validity concerns were addressed in the methodology chapter, there are inevitable limitations associated with the study and the methods adopted. Despite purposeful case selection criteria, and the evaluation interviews conducted to establish external validity, the sample size of case studies is a limitation. The case study phase of the research provides an in-depth investigation of two ETO systems. Both systems are from the construction sector. The evaluation interviews were designed to gather evaluative data from interviewees outside of these two systems, but within the construction sector. While this research strategy does bolster the case for generalisability, any claims must be made with caution.

A further limitation related to the issue of sampling is the coverage of ETO sectors in the study. The literature review highlighted a range of sectors associated with the ETO supply chain. While potential interviewees were targeted from a range of construction sectors, the full range of construction companies is not accounted for. The interviewees do, however, fulfil the range of organisational types hoped for including clients, manufacturers, network co-ordinators, design, logistics and organisational bodies.

While every effort to address construct validity concerns has been made, there is a subjective element in the research process that must be acknowledged. Triangulation techniques, interview questions grounded in the literature, brainstorming sessions, and prolonged engagement with case companies were some of the techniques used to ensure construct validity. Key industry contacts review case reports and project outputs. Process maps co-created and cross checked with industry, and interview transcripts were cross checked by industry. Progress presentations were also regularly delivered to industry and academic collaborators and the overall findings were examined for construct validity through the evaluation interviews. However, as many of these techniques rely on subjective perceptions, it is difficult to provide hard 'proof' that the models, classifications and concepts are an accurate picture of reality. It is hoped that the techniques described above, together with a transparent data collection and analysis process, provide a robust response to construct validity concerns.

9.7 FURTHER RESEARCH

This research has added structure to a relatively unchartered research field. Hence, a range of future research avenues can be identified. Constraints relating scope, time, finance and access prevented the uptake of these areas. First and foremost, to address the lack of coverage of all ETO sectors, evaluation interviews in other ETO sectors, such as shipbuilding, tool making and high technology would add to the potential to generalise to all ETO sectors. In addition to this, a number of key areas for development are identified.

Further research could be undertaken that would help to develop a more accurate definition of the ETO supply chain. These are as follows:

- Where are the decoupling points within the design stage? The structured literature review highlighted that decoupling points may exist in the design stage of the ETO supply chain. This was re-iterated in the evaluation interviews, showing that practitioners also recognise that there may be strategic buffer points within the design process.
- How can project classifications be incorporated into ETO supply chain definitions? Various project classifications are proposed in the literature. Given that the ETO

supply chain operates in a project environment, due consideration of project type would add to strategy formulation. Building on the findings of chapter 4, a further avenue that could be pursued is the factors that differentiate the mix of uncertainties in individual projects.

The evaluation interviews identified fruitful areas for further research relating to the assessment of flexibility requirements and the application of this in industry. These are as follows:

- How much flexibility is required? This research has identified which flexibility types are required and a methodology for identifying these requirements. It has not identified how much of each flexibility type is required.
- How much does flexibility cost? As identified in the evaluation interviews, a cost-benefit analysis of the flexibility types would support further commercialisation.
- An assessment tool for current flexibility capabilities would also help companies to diagnose current state, and match this against the desired state that is identified in this research.
- These follow-on studies could be supported by action research projects implementing flexibility re-engineering programmes in industry. This would involve re-engineering supply chains with more appropriate capabilities for managing uncertainties and observing the effectiveness of these changes.
- The conceptual model for supply chain flexibility could be applied and researched in different industries.

A final area that would be fruitful for more research is 'when to reduce and when to respond to uncertainty'? This thesis focussed on the response to uncertainty in ETO supply chains, and in doing so has addressed a gap in the literature. The reduction of uncertainty as an approach to managing uncertainty has been previously addressed by researchers in other areas of supply chain management (Childerhouse and Towill, 2004). A fruitful area of research would be to integrate these two approaches.

9.8 CONCLUSIONS

In this final chapter, the primary aim of the study has been discussed along with the findings for each of the research questions. The academic contributions have been summarised along with the implications for practitioners. The chapter has also presented the limitations and areas for future research.

SUMMARY OF CHAPTER 9 AIMS

1. **Articulate concise answers to each of the research questions**
   - Concise answers for each of the 4 RQs have been articulated
2. **Summarise the research findings in relation to the primary aim of the thesis**
   - The primary aim has been revisited and each chapter has been summarised
3. **Identify the academic contributions**
   - 5 principal contributions have been identified
4. **Identify the implications for practitioners**
   - These have been summarised, but are covered in greater depth in chapter 8.
5. **Identify the limitations and areas for further research**
   - Limitations have been identified. The need to cover a greater range of ETO sectors was noted
   - Further research has been identified in relation to ETO definitions and flexibility assessment

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APPENDICES

APPENDIX 1 - OVERALL PROJECT DESCRIPTION AND PROTOCOL

Main Research Proposition	*Supply chain flexibility can enable ETO supply chains to cope with project uncertainties*
Initial Research Questions	1. What is an ETO supply chain? 2. What are the sources of project uncertainty? 3. What are the coping mechanisms for uncertainty? 4. How can pipelines in ETO supply chains be improved? 5. How can the network of suppliers be configured to cope with uncertainty?
Units of analysis	• Network Co-ordinator – the company that assumes responsibility for configuring the network of suppliers, subcontractors and interdependent organizations that work together to deliver projects. • Projects – a selection of current projects in the network co-ordinator's portfolio • Pipelines – the activities between an order being placed with a supplier and the order being delivered.
Data Collection Techniques	Interviews, process mapping, observations, brainstorming sessions, archival data
Sequence of Activities	1) General Introduction - Organise interviews with major process teams to gain understanding of the system, the organisational structure and the type of projects in the system. - Identify subsystems 2) Project Identification - Develop criteria for project selection 3) Project Data Collection - Obtain programme and documents for each of the chosen projects - Organise site visits and interviews with site management to gather data on risk and uncertainty 4) Supplier Identification - Develop criteria for supplier selection - Organise site visit to supplier to undertake 'pipeline survey' (see appendix 4) 5) Supply Chain Management - Understand the systems and processes in place for managing subcontractors and suppliers - Investigate the role of supply chain flexibility 6) Organise Brainstorming Sessions - Consolidate uncertainty data collected from projects
Data analysis	Cross case analysis, process mapping, interview coding, quantification, descriptive statistics, cluster analysis, brainstorming and cause and effect analysis

Deliverables and dissemination	1) Case study report 2) Feedback presentations to McCLOSM and participating companies 3) Professional journals 4) Conference papers 5) Journal papers
Relevance to Organisations	- Independent view of supply chain for participating companies - Transfer of academic thinking/elements of best practice - Able to demonstrate commitment to best practice/continuous improvement - Possibility to learn from other construction operations - Cross-learning between industrial partners
Project Governance	*R (responsible)* – Mr Jonathan Gosling *A (accountable)* – Professor Mohamed Naim *C (consulted)* – Mr Nicholas Fowler, Mr Brain Moone, Dr. Robert Mason, Dr Andrew Potter, Professor Andrew Fearne *I (informed)* – Dr. A. Glanfield, Dr Andrew Davis, McCLOSM team

APPENDIX 2 - LOG OF INTERVIEWS FOR NETWORK CO-ORDINATORS

Network Coordinator 1 – Projects 1,2 and 3		
Project Reference	Date	Industrial Secondment: 10 weeks total spent at network co-ordinator 1.
	11/4/06	Interview • Business Improvement Manager • Scope, scale and focus of case study research
	28/11/06	Interview • Business Improvement Manager • Data collection requirements • Secondment and timing plans
Project 2	30/6/06	Project Manager (project 2) • The role of a project manager • Overview of project 2
	4/7/06	Interview • Supply Chain Manager • Purchasing Models • Key Performance Indicators • The sourcing database • Supply Chain Processes and Systems
Project 1	6/7/06	Site Visit to Project 1 • Meeting with Project manager & Site Manager • Guided tour of the site by the site manager • Profile and description of the project • Inspection and discussion of project plans • Requisition forms and processes • Material Procurement and Suppliers
	11/7/06	Brainstorming Session. • Business development team (5 People) and academic collaborator • Scope, scale and focus of case study research
Project 1	14/7/06	Interview • Quantity Surveyor • Work package preparation and pricing • The tender process • Work packages in Project 1 • Problems, risks and uncertainty in project 1
Projects 1, 2 and 3	19/7/06	Interview • Buyer • Material procurement • Use of 'The Sourcing Database' • Requisition forms and processes
Project 1	29/5/07	Site Visit to Project 1 and Brainstorming Session • Site Manager, Project Manager, Quantity Surveyor, Technical Manager.

		• Identify and consolidate supply chain uncertainties
Project 2	19/7/07	Quantity Surveyor • Work package preparation and pricing • The tender process • Work packages in Project 2 • Problems, risks and uncertainty in project 2
Project 2	21/7/06	Site Visit to project 2 • Observation of team meeting (site manager, project manager, quantity surveyor and buyer) • Problems, risks and uncertainty in project 2
	26/7/06	Interview • Technical Manager • Pre-construction phases • Technical development • Relationships with Architects
	18/8/06	Observation/participation in team meeting • Business Improvement Team
	8/9/06	Interview • Business Improvement manager • Clarification of data.
Project 2	13/10/06	Site Visit to project 2 • Team meeting including Site manager, Project manager, Quantity surveyor and Buyer
	10/11/06	Brainstorming session • Academic from Kent Business School, Business improvement Manager, Project Leader. • Scope, scale and focus of case study research
	15/3/07	Interview • Business Improvement Manager.
Project 2	17/4/07	Site visit to project 2 • Watch deliveries of pre cast concrete from the focal supplier in pipeline C
Project 2	17/4/07	Brainstorming session • Project manager and site manager • Identification of supply chain uncertainties
	11/12/08	Interview • Business Improvement Manager • Feedback presentation • Identification of next steps.
Project 3	13/1/09	Site Visit to Project 3 • Site managers and business improvement manager • Visit to different phases of the project
Projects 1, 2 and 3	13/1/09	Brainstorming session • Business Improvement Manager, Supply Chain Manager, Project Manager • Identify and consolidate supply chain uncertainties • Identify cause and effect of uncertainties
		Network Coordinator 2 – Projects 4 and 5

	28/3/07	Business Unit Director • Introductory Meeting • Scope, timings and aims of project
Project 4	26/5/07	Site visit to project 4 • Project Manager, Business Unit Director
Project 5	27/5/07	Site visit to project 5 • Project Manager, Site Manager and Business Unit Director
	5/1/08	Interview • Business Unit Director • Purchasing Models • Key Performance Indicators • Supply Chain Processes and Systems
	12/1/08	Executive Meeting for Suppliers & Brainstorming session • Group Director, Mechanical and Electrical Director, Business Unit director, 15 suppliers • Identify and consolidate supply chain uncertainties • Identify cause and effect of uncertainties
	16/1/08	Interview • Business Unit Director
	6/7/08	Interview • Business Unit Director • Presentation Feedback
Projects 4 and 5	24/11/08	Business Unit Director – Logistics • The role of logistics in construction supply chains • Barriers to success • Effective logistics
Projects 4 and 5	24/11/08	Brainstorming session • Business unit director and logistics manager • Cause and effect of uncertainties • Identify likelihood and impact of uncertainties
Both Systems		
Projects 1, 2, 3, 4 and 5	14/1/09	Brainstorming session • Business Improvement Manager, Business Unit Director, Logistics Manager • Verify list of uncertainties and cause and effect diagram • Match uncertainties with flexibilities • Confirm likelihood and impact of uncertainties

APPENDIX 3 - PROJECT UNCERTAINTY DATA COLLECTION PROTOCOL

Aims and Objectives: Identify Uncertainties at different stages during the project life cycle
Research Question Addressed: What are the sources of uncertainty in engineer-to-order projects?
Protocol:

1. Identify project
2. Gain an understanding of the project using documentation and informal interviews with relevant employees
3. Organise site visit and interviews with site management
4. Use project uncertainty data collection template to gather data relating to project uncertainties

The data collection template is shown on the following page:

Project Uncertainty Data Collection Template **Project:** **Interviewee:**		
Standardised Project Phases (as defined by Winch and Carr)	**1) What are the risks and uncertainties for this project during the following stages?** **2) Where does this uncertainty Originate from?** **3) How could this uncertainty be mitigated?**	**1) In your experience, what are the general risks and uncertainties experienced during the following project stages?** **2) Where does this uncertainty Originate from?** **3) How could this uncertainty be mitigated?**
Define Need		
Establish Viability		
Conception		
Scheme Design		
Detailed Design		
Production Planning		
Construction (Main Trades)		
Construction (Finishing Trades)		
Commissioning		
Facility Management		

APPENDIX 4 – THE PIPELINE SURVEY

The research protocol is as follows:

1. Identify Company
2. Arrange interview and site visit
3. Present introductory slides
4. Conduct Interview
5. Site Visit
6. Write up interview notes and notes from site tour
7. Data analysis – Coding of interview data.
8. Data analysis – Develop process maps.

PIPELINE SURVEY		
Company Details		
Name:	Company:	Date:
Position of Interviewee:		
No of Employees:	Turnover:	
Trade:	Project working on in system:	
Products and Services		
Key Markets? Product and Service Range? Areas of Responsibility: Labour, Installation, Plant, Materials, Design, Delivery? Geographical area covered?		

Project Interface
Description of works being undertaken:
Responsibilities: Labour/Plant/Materials/Design/Delivery
Other trades interfacing with (Any issues here?)?
Plant and Equipment Requirements?
Labour requirements?
Information requirements?
Materials and Suppliers
Materials (what type, who supplies, who responsible for ordering, trigger for ordering):
Key production inputs?
Stock held in days?
Central vs project stock?

What form is the stock held in? Generic? Work in progress? Finished goods?
Buy from stock or made to order?
How do you manage your supply chain?
Key Performance Indicators for suppliers?
How do you forecast supply requirements?
Production
What is the supply chain structure (Show and discuss supply chain structure diagram and table showing attributes of supply chain structures). Prompt interviewee to relate this to their own operations.
Make to stock vs Make to order?
Planning System/IT System?
PROCESS STEPS: Main Production Steps (suggest drawing brief process map)?

Please could you describe the manufacturing process? Inbound logistics? Outbound logistics? Key production inputs?
Is any of the assembly outsourced?
Customer Profile
Main Customer/Client Profile: Repeat framework agreements or one offs? How do you manage relationships with customers? Collaborative forecasting? Do you support your customers with bid development?
Strategic Capabilities
FLEXIBILITY CAPABILITIES: New Product Flexibility?

Mix flexibility? Volume Flexibility? Delivery Flexibility? Access Flexibility?
What are the sources of competitive advantage?

Lead Time Activity:	Enquiry	Design	Approval	Proc-urement	Manu-facture	Stocks	Transport	Site Storage	Site Integration
What amount of time would you estimate that the following contributes to the LT of product? Optimistic/Most likely/Pessimistic estimate?									
What are the key problems/risks/uncertainties along the chain of activities?									
What might help to overcome these issues?									

Overall LT	
Optimistic LT	
Most Likely LT	
Pessimistic LT	

APPENDIX 5 - INTERVIEW LOG FOR PIPELINE SURVEY

Date	Product	Interviewee(s)	Factory Visit
7/7/06	Windows	Account Manager	
27/7/06 3/10/06	Pre-cast Concrete	Account Manager Operations Manager and Site Manager from Network Coordinator	 1
4/10/06	Metalwork	Managing Director	
9/10/06 30/1/07	Lift	Account Manager Regional Sales Manager	
12/4/07	Roof Trusses	Operations Manager	1
27/06/07	Brick and Block	Sales Executive & Divisional Director	
11/6/08	Paint	Managing Director	1
26/6/08 13/1/08	Modular Bathrooms	Business Development Manager Presentation at Supplier training day	1
9/7/08	Drylining and Safety	Chief Estimator	1
22/1/09	Doors	Account Manager	
29/1/09	Timber Frame Systems	Sales Manager, Project manager & CAD engineer	1
2/2/09	Timber	Account Manager	

APPENDIX 6 – INPUT-OUTPUT DIAGRAM