AN EXPLORATION OF LEAN THINKING FOR MULTI-STORREY TIMBER HOUSING CONSTRUCTION
CONTEMPORARY SWEDISH PRACTICES AND FUTURE OPPORTUNITIES

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DOCTORAL THESIS

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I

PREFACE

...in the distance the gateway marking the end of the road looms. Barely visible at the roads edge, an old man sits alone besides a fireplace and beckons for me to join him. I hesitantly walk over and sit down beside him. Before I have a chance to speak the old man addresses me in a firm tone – *Is this the end of the road?* Is this the end of the road...for me? What does the old man mean? I hesitate in answering. Before my thoughts can be formulated into words, the old man glances at me. With an understanding smile he says – *You are truly ready to go forward into the unknown!*

Finally, I came to understand that this journey will never truly end; in fact each stop on the journey is just the beginning of the next. Once the walking stick is picked up there is no stopping the mind from continuously yearning for more knowledge. Of course, this sometimes fascinating and at other times dreadful journey into the world of knowledge can not be done alone. Without the time and devotion of numerous people I would never have arrived at this stage:

- First and foremost, I wish to thank my supervisor Lars Stehn, who has believed in me from the start of this long and twisting journey, especially at times when I have doubted myself. Without your devotion and support this research would have ended like it begun, as a good idea. For this you have my deepest gratitude.
- During all these years my family has stood by me and provided support when I needed it the most, without asking for anything in return. Even though I have sometimes failed to acknowledge this support it has been invaluable to me.
- I wish to thank my colleagues at the Division of Structural Engineering – Timber Structures for the harmonic research environment you provided and all the fun we have had over the years. I hope the ‘Woodpecker’ and ‘Träskalle’ eras will not be forgotten and that a suitable person steps forward to pick up the torch.
- Finally, I wish to thank once more all my Norrathian friends for providing me with so much fun in times of darkness. This is the reason for my grumpiness and bad moods. If you ever read this then I am sure you will understand.

I also wish to acknowledge the numerous people, companies and organization that have made this research project possible. Without any specific order I extend my gratitude to Jenny Sundqvist, Sunna Cigén, Eric Liljeström, NCC AB, Mitthem, Lindbäcks Bygg AB, Martinsons Trä AB, Kempestiftelsen, Lars Erik Lundbergs Stipendiestiftelse, Åke och Greta Lissheds Stipendiestiftelse, Svenska Byggbranschens Utvecklingsfond.

Luleå, November 2006

Anders Björnfot
“...what should have been done in haste yesterday
is better done in calm tomorrow...”
ABSTRACT

Construction is affected by a large amount of waste (up to 35% of production costs in Sweden) and adverse relationships that have led to low quality and profitability. In Sweden, industrialized construction is viewed as one solution to the construction issues that have led to numerous development efforts. Based on the success of Lean Production in manufacturing and the development of Lean Construction in countries such as Brazil, Denmark and the USA, the application of Lean Construction is currently debated in Sweden. However, Lean Construction theory seems unable to explain the development of industrialization in Swedish construction. Consequently, there is need for further research on how to better match industrialized construction with Lean Construction theory.

The aim of this research is twofold; 1) explore how Lean Construction theory can be used to gain a deeper understanding of Swedish multi-storey timber housing construction and 2) explore how knowledge of contemporary practices can help extend the theory of Lean Construction to provide a deeper understanding of industrialized construction. There is presently a Swedish governmental campaign supporting the development of timber housing construction. Consequently, this is a good opportunity to explore the applicability of Lean Construction. Based on an understanding of the Lean philosophy, contemporary Swedish timber construction practices are analysed through three case studies, viz. element prefabrication, volume prefabrication, and an initiative combining volumes and elements.

The driving force in the development of applications for Lean Construction is production system design for increased control over construction events – stability (reliability) and better control (predictability) are sought by reducing the variety in working practices, supply chains, etc. Consequently, improving work-flow is the primary goal of Lean Construction. An analysis of contemporary timber element prefabrication reveals three main issues – 1) complicated design decisions, 2) poor design documentation, 3) deficient production planning that, from a Lean perspective, obstruct work-flow. However, the root cause of work-flow issues is identified as a lack of value management, thus causing ripples throughout the production system resulting in variety and poor control.

Results from volume and volume/element prefabrication indicate that value management greatly improves production system design. These well-defined technical platforms, so-called ‘product offers’, represent a new way of thinking in delivering value for multi-storey housing construction. The Lean characteristics of the ‘product offer’ are product specifications based on customer value, value stream management through specific resources and activities, management of value-adding activities for flow, flexibility to customer demands enabling pull, and transparency for continuous improvements (perfection). Based on these characteristics, the ‘product offer’ is viewed as one possible change-agent in the adoption of Lean Construction for Swedish multi-storey housing construction.

Keywords: Industrialized timber construction, Lean Construction, Lean Thinking, Multi-storey timber housing construction, Prefabrication
SAMMANFATTNING


Målen med denna forskning är; 1) undersöker hur Lean Construction teori kan användas för att ge en djupare förståelse för byggandet av flerbostadshus i trä, och 2) undersöker hur en förståelse för industriella Svenska produktionsmetoder kan utveckla Lean Construction och underlätta forskning inom industrialiserat byggande. För närvarande pågår en nationell regeringsledd kampanj för att främja träbyggandet. Därför är detta en bra tidpunkt att undersöka vad en förståelse för Lean Construction kan medföra för det svenska träbyggandet. Baserat på en förståelse av Lean filosofin har tre nutida svenska produktionsmetoder analyserats via fallstudiier, prefabricerat byggande med element, prefabricerat byggande med volymer, och ett nytt initiativ där volymer och element kombineras.

Ledande vid utvecklingen av applikationer för Lean Construction är ett bättre kontrollerat produktionssystem där stabilitet (pålitlighet) och bättre kontroll (förutsägbarhet) eftersträvas genom en reducering av variansen vid produktionen och inom leverantörsförsedjor. Därför är det främsta målet för Lean Construction att främja ett jämnt flöde av arbete. En analys av byggande med prefabricerade element avslöjar tre problem; 1) komplicerade design beslut, 2) undermålig dokumentation och 3) bristfällig produktionsplanering. Från ett Lean Construction perspektiv representerar alla dessa hinder för ett jämnt arbetsflöde. Men det verkar som om det huvudsakliga problemet är en bristande specificering och hantering av produktvärde tidigt i bygghandelns process vilket påverkar flödet inom whole produktionssystemet.

Resultat från volym och volym/element fallstudierna pekar på att en god hantering av produktvärde väsentligt förbättrar hela produktionssystemet. Dessa väldefinierade tekniska plattformar (‘produkt erbjudanden’) representerar ett nytt tankemönster vid hanteringen av värde vid byggandet av flervåningshus i trä. ’Produkt erbjudandet’ består av ett flertal Lean karakteristika; specifikation av produkter baserat på kundens värde, identifiering av resurser i hela värdekedjan, hantering av värdeskapande aktiviteter för flöde, tillgodoseende av kundbehov via flexibilitet (dragande system), och transparens för kontinuerliga förbättringar (perfektion). Därför kan ‘produkt erbjudandet’ anses representera en möjlig strategi för införandet av Lean Construction vid Svenskt byggande av flervåningshus.

Nyckelord: Industrialiserat byggande i trä, Lean Construction, Lean Thinking, Flervåningshus i trä, Prefabricering
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# APPENDICES

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Interview questions with site workers

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1 INTRODUCTION

This chapter contains the introduction to the research presented in this thesis, i.e. background, research area, research motives, aim, objectives, limitations, disposition, and content overview.

1.1 Background

Recent studies have raised concern about the condition of the Swedish construction industry, i.e. low quality, high construction costs, low profitability and lack of innovations (e.g. SOU 2002). Josephson and Hammarlund (1999) identified the cost of construction defects to be up to 10% of the production costs; about 30% of the costs originated from design, 40% from site work, and 20% from machines and materials. In 2005 the persistent high construction costs were again in focus in the construction industry. Josephson and Saukkoriipi (2005) identified that waste (activities that do not provide any value and should be avoided) account for up to 35% of the production costs. According to the authors, there seems to be a conviction among Swedish construction practitioners that the structure of construction is unique (e.g. many different participants, one-of-a-kind projects, a conservative industry, etc.), which is not only considered a cause in generating waste but also a hindrance for industry development. Construction industry related issues are certainly not unique to Sweden, since both the Egan report (Construction task force 1998) and Koskela (2000) presents similar issues, though from an international perspective.

In several Swedish publications (Olofsson et al. 2004a, Boverket 2005, Industrifakta 2006) as well as within the Swedish construction industry, industrialization is mentioned as one possible solution to the issues of construction. Lessing (2006) defined Industrialized house-building as ‘a thoroughly developed building process with a well-suited organization for efficient management, preparation and control of included activities, flows, resources and results for which highly developed components are used in order to create maximum customer value’. The application of industrialization as a solution to the problems of construction has not only been discussed in Sweden. Koskela (2003) claimed that industrialization of construction is a useful concept in reducing non-value adding craft-based activities. Consequently, industrialization seems to be a possible solution to reduce the large amount of waste in construction. For this purpose, construction researchers have directed attention towards the manufacturing industry in an attempt to learn, or in some cases even copy, successful concepts (see e.g. Gann 1996, Crowley 1998).

Besides the concept of industrialization in Swedish research, other development efforts and applications of construction research inspired by manufacturing are, for example, logistics (Agapiou et al. 1998), agile production (Naim and Barlow 2003), and supply chain management (London and Kenley 2001). Koskela (2003) argues that the application of renewal concepts for construction has often failed due to the increased complexity in the management of construction projects compared to the production of manufactured goods. However, one specific manufacturing theory – Lean Production (Womack et al. 1990) –
has become an addition to construction management research. In the automotive industry, Lean Production has been successful in improving quality and lowering costs. Koskela (1992) introduced this research field in construction, which has internationally become known as Lean Construction. This theory is further considered in this thesis.

A common academic view of Lean Construction is a new way of thinking (a philosophy) whose purpose is to challenge the traditional understanding of project and production management (Ballard and Howell 2004). Bertelsen (2004) state that the aim of applying the Lean philosophy for construction is to deliver the product to the customer while maximizing value and minimizing waste. During recent years, focus within the Lean Construction research community seems to have shifted from theory building and identifying construction issues to working on and implementing solutions: refer to the proceedings from the conference on Lean Construction (IGLC 2006). Lean Construction research has led to the development of methods and tools for improved execution of construction work; one often cited tool is the Last Planner System of production control which enables Lean practices in site production (Ballard 2000). By improving the management and execution of construction work, Lean Construction research seems to be a complementary approach to research on industrialized construction.

1.1.1 Swedish timber housing construction context

In Sweden, the amount of newly produced houses/apartments per million inhabitants is the lowest in Europe (SBI 2005). However, as the cost for apartments rises the demand for new residences is steadily growing. There is a clear trend in recent years of an increased production volume of multi-storey residences (SBI 2005). Ever since the revised function based building regulations were introduced in Sweden in 1995, timber has slowly gained acceptance among construction practitioners as a suitable material for multi-storey housing construction. Spurred by the published report ‘More timber in construction’ (DS 2004), there is currently an increasing interest in the development of structural timber systems and other ways to use more timber in multi-storey housing construction. The move from production of a limited amount of prototype timber frame multi-storey houses to the niche market position of today (Brege et al. 2004) illustrates this trend with several types of prefabricated timber frame systems (roughly estimated to 10–15% of the market).

Production of multi-storey timber housing in Sweden can be categorized by three distinct production methods (Figure 1.1) – stick built, assembly using prefabricated timber elements (Sardén 2005), or assembly using prefabricated timber volumes (Höök 2005). In reality, each constructed building utilizes a combination of production methods. However, when constructing multi-storey timber housing it is common to focus on one production method for its erection, such as elements or volumes. Consequently, an understanding of Swedish timber housing construction involves the prefabrication of construction products as well as on-site, traditional construction work (Björnfot 2004).
CHAPTER 1 INTRODUCTION

Figure 1.1 Common production methods for multi-storey timber housing construction.

Based on the state of the construction industry and the current interest in developing multi-storey timber housing construction, this specific type of construction is interesting as a research topic in this thesis because:

- Building in timber through extensive use of prefabrication is thought to be a driver in lowering the overall building costs and providing new products with a potential for cost reductions of about 30% (Brege et al. 2004). This development is beneficial from an overall construction efficiency perspective.

- Timber as a material is suitable for the manufacturing of prefabricated building components. Swedish single-family detached housing manufacturers have dominated for decades and have shown the possibility of efficient detached timber housing manufacturing using cost-effective methods (Bergström 2004).

- An increased use of timber in construction helps reduce the environmental impact of construction. Therefore timber is of great relevance from an environmental perspective, since it is a reproducible raw material (Stehn 2002). Industrialized multi-storey timber housing construction is a development initiative that strives to use more timber in construction.

- Numerous Swedish industry initiatives are currently developing new structural systems for multi-storey timber housing construction (see e.g. Larsson et al. 2004, Höök 2005, Lessing 2006), serving as good sources of empirical data collection and methodological advancement of industrialized construction.

- In addition to small- to medium-sized contractors specializing in multi-storey timber housing construction, there is also an increasing specialization trend among all large contractors (NCC, Skanska and PEAB) that serves as an example of ongoing construction development benefiting from research in industrialized construction; e.g. the development of “NCC KOMPLETT” (NCC 2006).

In my licentiate thesis (Björnfot 2004), industrial methods relating to modularity and buildability were explored in relation to long-span timber structures. Due to the low complexity in structural design and customer involvement in this type of structure it was argued that a deeper understanding of the applicability of manufacturing concepts for construction must be evaluated through a study of more advanced building types. In this regard, multi-storey timber housing construction was argued to represent the natural “next step” due to the increased complexity in the number of construction components, functional requirements, and participants involved.
1.1.2 Why Lean Construction?

In my licentiate thesis (Björnfot 2004), Lean Construction was already promoted as being able to deal with the issues of construction by improving the value delivery process. Theoretical advancement and practical development of Lean Construction is of central interest in this research because:

- In manufacturing, the Lean philosophy is advantageous in increasing quality, profitability and customization (Womack et al. 1990). These aspects are also critical for the future development of industrialized construction (Lessing 2006).
- Ever since the introduction of Lean Construction, the international academic Lean Construction circle has been developing theory and applications, i.e. International Group for Lean Construction (IGLC 2006), Lean Construction Institute (LCI 2006), and Lean Construction Journal (LCJ 2006). There is a strong belief in these sources that the Lean philosophy can act as a mechanism to reduce wasteful activities by improving the management of construction.
- As a result of Lean Construction research, methods and tools are already being used in practice in a number of countries, e.g. the USA, Brazil and Denmark (Ballard and Howell 2003), where they have helped change and improve how production in construction is managed and executed. The same development trend is also evident in other countries.
- In Sweden, the application of ideas from Lean Construction is currently being debated and its philosophy is slowly emerging as a possible concept to improve the value delivery process. Lean Construction is also being used by a number of Swedish companies (e.g. NCC 2006, ARCONA 2006) and Sweden recently entered as a member of the international Lean Construction community – the Lean Construction Institute.

An in-depth theoretical study of Lean Construction and its application for the Swedish construction industry should obviously be of interest for both national academics and practitioners. Swedish research on industrialized construction, mainly concerning volume prefabrication (e.g. Bergström 2004, Höök 2005, Lessing 2006), briefly cover the applicability of the Lean philosophy. However, these sources do not extensively cover the Lean Construction theory, but rather mainly involve specific Lean Production concepts such as Just-in-Time and continuous improvements. Based on its long development, the understanding of Lean Construction seems to have moved past Lean Production for a theory of its own (Bertelsen 2004). What this (new) theory can do to increase our understanding of industrialized construction has neither been currently dealt with extensively in the Lean Construction research community nor explicitly in Swedish research initiatives.
1.2 Research motives

Already during the study of the long-span timber structure production process in my licentiate thesis (Björnfot 2004), methods and tools developed within the Lean Construction community were found unable to fully explain the industrialized construction process. Therefore, concepts such as modularity and buildability were used to explain the observed events (see Paper I). Surprisingly at that time, Lean Construction theory was lacking, since it had been promoted as a new way of thinking for construction in general. Ever since initiating this study of Swedish industrialized multi-storey timber housing construction, there has been a growing feeling of Lean Construction as being unable to fully explain how this industry has evolved. The complexity discussion (see e.g. Bertelsen 2004) and the applications of Lean Construction theory, for example the Last Planner System, do not seem to be developed for or readily applicable to the Swedish industrialized construction process.

Research on industrialized construction in relation to Lean Construction is occasionally met with scepticism from the Lean Construction research community. For example, Koskela (2000, p.232-233) argues that the variety of prefabrication is greater than in site production, the amount of design required is larger and has to be done earlier, and the error correction cycle is longer. Koskela concludes that the total process of industrialized construction tends to become more complex and vulnerable in comparison to site construction. However, Koskela notes that industrialization is relevant as a source of future productivity improvements. Consequently, further research on how to better match industrialized construction with Lean Construction theory is needed.

Is Lean Construction a relevant research field for the Swedish multi-storey timber housing industry? Considering the positive effects of Lean Production on the manufacturing industry in improving, for example, quality and profitability, the industrialized construction process could then be improved through the Lean philosophy. Also, considering the general efficiency of Swedish industrialized construction (judging by the strong market grip and the profitability of single family detached housing manufacturers) and its current development, Lean Construction theory could benefit from empirical studies in this field. Such studies could extend Lean Construction theory to include knowledge of how industrialized construction can be better managed and improved.

1.3 Aim and purpose

Based on the research motives the aim of this research is twofold;

- Explore how the theory of Lean Construction can be used to gain a deeper understanding of the Swedish multi-storey timber housing production process and how this process can be improved through Lean Construction theory.
Explore how knowledge of the contemporary Swedish multi-storey timber housing production process can help extend the theory of Lean Construction to provide a deeper understanding of industrialized construction.

To reach these aims, the purposes of this thesis are:

1. Understand what the Lean philosophy implies for construction by studying its fundamentals – Lean Production, Lean Thinking and Lean Construction.
2. From this theory, develop a theoretical framework representing a comprehensive understanding of Lean Construction theory.
3. Study the contemporary Swedish multi-storey timber housing production process from the perspective of Lean Construction theory.
4. Identify key issues of multi-storey timber housing construction that can be better understood from a Lean Construction perspective and then devise solutions to these issues.
5. Identify aspects from contemporary Swedish multi-storey housing construction that can contribute to a more comprehensive theory of Lean Construction.

1.4 Scope of research and limitations

Similar to the work in Björnfot (2004), the design process is not of interest per se. In this work it is the result of the design process – the product design – that is of interest, since it is this that affects the execution of production. Consequently, this research focuses on the production phase including production planning, manufacturing, logistics, and site assembly. Other construction phases not directly related to production, such as tendering and maintenance, are not explicitly considered. Instead these phases are briefly discussed where deemed relevant for an in-depth understanding of observed events, such as the influence of clients on product design and hence the execution of production.

The research performed and presented in this thesis is limited to Swedish conditions within multi-storey timber housing construction. As such, an international viewpoint is not provided. This limitation exists because the Swedish construction industry is at the frontline on industrialized multi-storey timber housing construction from the perspective of both practice and research. Therefore, increasing the knowledge of timber housing construction is best achieved by studying the Swedish industry and its practices. Of course timber is not the only material of relevance for industrialized construction. However, the advance of timber construction knowledge and applications is essential for my research subject (timber structures).

The considered theory in this research is limited to understanding the Lean philosophy (Lean Production, Lean Thinking and Lean Construction). However, the Lean philosophy
CHAPTER 1  INTRODUCTION

is not a complete theory by itself, since it makes use of concepts from other production and management theories, such as Total Quality Management. Therefore, providing a description of a Lean philosophy not influenced by other theoretical fields is unavoidable. Based on the discussion in the theoretical section (Chapter 2.5), the analysis section mainly considers the flow and value principles of the Lean philosophy. No quantification of these principles has been performed in this research, since its primary aim is to provide an understanding of Lean Construction theory in relation to industrialized construction rather than a detailed study of specific applications and their impact.

1.5 Contents and disposition

The contents of this thesis are based on the results presented in the five appended papers (briefly outlined below) and their combined analysis within this thesis. The disposition of the thesis contents is outlined in Table 1.1.

**Paper I.** “A DSM approach displaying structural and assembly requirements in construction”. This paper, containing the condensed results of my licentiate thesis, was written with Lars Stehn. In January 2006, the paper received acceptance for publication in the Journal of Engineering Design. I performed the case study as well as wrote the majority of the paper contents, while the analysis was performed with the co-author.

**Paper II.** “Product design for improved material flow – a multi-storey timber housing project”. This paper was written with Lars Stehn. The paper was presented at, and published in the proceedings of, the 13th Annual Conference of the International Group for Lean Construction, Sydney, Australia in July 2005. I performed the case study as well as wrote the majority of the paper. The analysis was performed with the co-author.

**Paper III.** “Application of Line of Balance and 4D CAD for Lean Planning”. This paper was written with Rogier Jongeling. In July 2006, the paper received acceptance for publication in the journal of Construction Innovation. My main contribution to the paper was performing the case study. The analysis of the case study results and the majority of writing the paper contents were performed with the co-author.

**Paper IV.** “Prefabrication: a Lean strategy for value generation in construction”. This paper was written with Ylva Sardén. The paper was published in the proceedings of the 14th Annual Conference of the International Group for Lean Construction, Santiago, Chile in July 2006. I performed the case studies, while the analysis and paper contents were written with the co-author.
Chapter 1 Introduction

Paper V. “Value delivery through product offers: A Lean leap in multi-storey timber housing construction”. The paper was written with Lars Stehn. In September 2006, this paper was submitted for possible publication in the Lean Construction Journal and since then has undergone one review phase. I performed the case studies and wrote the majority of the paper contents, while analysis was performed with the co-author.

Table 1.1 Disposition and contents of this thesis.

<table>
<thead>
<tr>
<th>CHAPTER</th>
<th>CONTENTS</th>
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<tbody>
<tr>
<td>1. Introduction</td>
<td>This chapter contains the introduction to the research presented in this thesis, i.e. background, research area, research motives, aim, objectives, limitations, disposition, and content overview.</td>
</tr>
<tr>
<td>2. Theoretical context</td>
<td>The theory section deals with the evolution of Lean Production, the five principles of Lean Thinking, and their application for production in general and for construction specifically. This section finally presents a theoretical framework as an aid in empirical data collection and analysis.</td>
</tr>
<tr>
<td>3. Research method</td>
<td>This chapter relates for how the research presented in this thesis has been performed, i.e. research strategy and data collection methods. As such, this chapter provides a starting point in guiding the reader through the contents of the empirical and analysis sections of this thesis.</td>
</tr>
<tr>
<td>4. Case study results</td>
<td>Chapter 4 presents case study results from element, volume and volume/element prefabrication which provide a basis for an understanding of contemporary Swedish construction practices. The results presented contain information from the design, manufacturing, logistics, and assembly phases.</td>
</tr>
<tr>
<td>5. Case study analysis</td>
<td>Chapter 5 provides a theoretical perspective on the case study results. Based on the understanding of Lean Construction (Chapters 2.4 and 2.5), this chapter analyses the applicability of the Lean philosophy for Swedish multi-storey timber housing construction.</td>
</tr>
<tr>
<td>6. Discussion &amp; conclusions</td>
<td>Chapter 6 discusses and concludes the results presented in this thesis. Answers to the two aims of this thesis are provided and the contributions are specified before future research opportunities are recommended. The research validity and the generalization of the findings are also evaluated.</td>
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CHAPTER 2 THEORETICAL CONTEXT – THE LEAN PHILOSOPHY

The theory section deals with the evolution of Lean Production, the five principles of Lean Thinking, and their application for production in general and for construction specifically. This section finally presents a theoretical framework as an aid in empirical data collection and analysis.

2.1 An introduction to the theoretical context

The theory is based on a literature survey of Lean Production, Thinking and Construction (Figure 2.1). To understand the application of the Lean philosophy for multi-storey timber housing construction, an understanding of how and why the Lean philosophy was developed is provided. The Toyota Production System is the foundation of Lean Production (Chapter 2.2) which in turn serves as the foundation for the Lean Thinking principles (Chapter 2.3). Lean Production and Lean Thinking both provide with important insights in the development and application of Lean in construction (Chapter 2.4). To understand the development of Lean Construction, the construction value delivery process provides important insights. Finally, the Lean philosophy is concluded and summarized as a ‘model of analysis’ (Chapter 2.5) which is used to explore the application of the Lean philosophy for Swedish multi-storey timber housing construction.

Figure 2.1 Overview of the theoretical context.

2.2 Lean Production

‘...the conversion to Lean Production will have a profound effect on human society – it will truly change the world’ (Womack et al. 1990, p.9-10).

A compilation of the evolution of Lean Production is presented in ‘The Machine that Changed the world’ by Womack et al. (1990). At the time of the worldwide Lean
revolution (1970’s to 1980’s), mass production was fully (or at least to a large extent) implemented among the majority of the manufacturing companies in North America, Europe, and Japan while craft production was visible at small specialized European manufacturers. Craft production implied directly dealing with customers and providing them with a unique image, while mass production implied strict attention to interchangeability, simplicity, and ease of attachment for the most efficient way of producing large batches of goods, i.e. economy of scale (Kahn and Mello 2004). After a long time of success where the mass production philosophy was dominant, issues began appearing; already in 1955 the downslide began as U.S. mass production companies slowly began losing market shares to Japanese and European manufacturers (Womack et al. 1990).

Among the most severe problems with the mass production philosophy were the low status of the worker on the shop floor (eventually leading to union uproar), inflexibility to changes in demand (leading to growing inventories), and restricted product offers (leading to a loss of market shares as competition was introduced). The Japanese auto manufacturer Toyota built on the success of the mass production system by reworking, improving and perfecting it to fit the needs of the Japanese auto market; in the 1950’s the Toyota Production System was born. Womack et al (1990) later founded the term Lean Production as a description of the Toyota Production System and its application by other Japanese manufacturers. The Toyota Production System was stated to be Lean because:

‘…[Lean Production] uses less of everything compared with mass production – half the human effort in the factory, half the manufacturing space, half the investment in tools, half the engineering hours to develop a new product in half the time. Also it requires keeping far less than half the needed inventory on site, results in many fewer defects, and produces a greater and ever growing variety of products’ (Womack et al. 1990, p.13).

To obtain these results, Lean production manages and improves on the work in manufacturing, product development, supply, and distribution. Condensed from Womack et al. (1990), Figure 2.2 illustrates the interactions between these phases and their purposes. A summary of the basic Lean Production principles utilized by the Lean Production system is provided by Oliver et al. (1994, 1996); Lean factory practices, team-based work organization, active problem solving, high commitment human resource polices, tightly integrated material flows, active information exchange, joint cost reduction, and shared destiny relations. Common Lean factory practices are small-lot production, waste reduction activities, visibility and transparency, Just-in-Time, standard work, single-piece flow, takt time, etc. (see e.g. Womack et al. 1990, Liker and Lamb 2002).

‘The Toyota Way’ (Liker 2004) provides with a more comprehensive description of the Toyota Production System. This description is based on 14 principles and practices aiding manufacturing companies in the transformation to Lean Production; 1) Base management decisions on a long-term philosophy, 2) Create continuous process flow to bring problems to the surface, 3) Use “pull” to avoid overproduction, 4) Level out workloads, 5) Stop to fix problems – get quality right the first time, 6) Standardize tasks for continuous
improvements, 7) Use visual control to uproot problems, 8) Use only reliable, thoroughly tested technology, 9) Grow leaders who thoroughly understand the work, 10) Develop exceptional people and teams who follow your company's philosophies, 11) Respect your extended network of suppliers by helping them to improve, 12) Go and see for yourself to thoroughly understand the situation, 13) Make decisions slowly by consensus; implement decisions rapidly, and 14) Become a learning organization through relentless reflection and continuous improvement. These principles (especially principles 9 to 11) stress the importance of teamwork throughout production systems and supply chains for the success of Lean Production (Figure 2.2).

![Figure 2.2 The essentials of Lean Production – condensed from Womack et al. (1990).](image)

In Björnfot (2004), the relation between Lean and other successful and well-known management theories was presented (Table 2.1). Based on Shah and Ward (2003) and Cristiansen et al. (2003), it was stated that the concepts promoted by Lean includes many of the characteristics from Just-in-Time (JIT), total preventive management (TPM), total quality management (TQM), and human resource management (HRM). It seems that not many Lean practices are new or fresh from a pure management perspective. However, Lean Production seems to be the first management theory able to bring all these theories together into a whole that benefits the whole organization, all the way from the worker on the shop floor, to the supply chain, and all involved stakeholders (Björnfot 2004).

Table 2.1 Lean practices from JIT, TQM, TPM, and HRM (Björnfot 2004).
Lean Production is not a unique concept from a pure production perspective either even though the Lean improvements realized by Toyota has been a ‘Holy Grail’ quest of many manufacturing companies and research communities worldwide; as examples, Panizzolo (1998) provides with a study of 27 manufacturers who has adopted Lean while Oliver et al. (1994) provides with a similar study of 18 auto-components plants in UK and Japan. However, the manufacturing improvements promoted by Lean Production are certainly not unique to Lean manufacturers. Quite a few of the mentioned Lean practices can be discerned from other industries without direct reference to Lean; good examples of which are computer manufacturing and distribution (Dedrick and Kraemer 2005) and the shipbuilding industry (Liker and Lamb 2002).

The Toyota Production System, from where the Lean ideas where originally developed, was fundamentally a new business model representing a framework of concepts and methods for enhancing corporate vitality (Fane et al. 2003), i.e. a conceptual innovation and a new way of thinking about production (Ballard and Howell 2003). As such, Lean Production can be considered a third way of production which draws on qualities from both mass (e.g. production efficiency) and craft (one-piece flow) production. It seems that Lean Production is about doing sound business (Soriano-Meier and Forrester 2002) since its implementation is influenced by industry structure and culture (Green and May 2005); Green (1999) argued that Lean Production is mainly suitable for the Japanese industry since it was primarily developed for Japanese conditions. Therefore, care should be taken in transferring the Lean Production philosophy to other industries, a point acknowledged by Womack and Jones (2003) in their development of the principles of Lean Thinking.

2.3 Lean Thinking

‘…[Lean Thinking] changes everything: how we work together, the kind of tools we develop to help with our work, the organizations we create to facilitate the flow, the kinds of careers we pursue, the nature of business firms and their linkage to each other and society’ (Womack and Jones 2003, p.52).

Viewing Lean Production as a way of thinking promotes its understanding as a philosophy where the goal is to provide customers with precisely what they want, when they want it, while continuously thinking about how things can be done more efficiently. Lean as a way of thinking was introduced by Womack and Jones (2003) in ‘Lean Thinking: Banish waste and create wealth in your corporation’ (first edition published in 1996) which has spurred the application of Lean practices in a multitude of different production settings. The essence of Lean Thinking, as presented by Womack and Jones (2003), are five principles that guide a company in Lean implementation. These principles (Table 2.2) are; 1) Precisely specify value in terms of a specific products, 2) Identify the value stream for each product, 3) Make value flow without interruptions, 4) Let the customers pull value from the producers, and 5) Pursue perfection.
CHAPTER 2  THEORETICAL CONTEXT – THE LEAN PHILOSOPHY

Table 2.2  The principles of Lean Thinking (condensed from Womack and Jones 2003).

<table>
<thead>
<tr>
<th>PRINCIPLE</th>
<th>CONCEPTUALIZATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>Lean Thinking must start with a conscious attempt to precisely define value in terms of specific products offered at specific prices to specific customers.</td>
</tr>
<tr>
<td>Value stream</td>
<td>The activities necessary to create, order, and produce a specific product so that they can be challenged, improved, and, eventually, perfected.</td>
</tr>
<tr>
<td>Flow</td>
<td>Tasks can be done more efficiently when the product is worked on continuously from raw material to finished good while all impediments to flow are removed.</td>
</tr>
<tr>
<td>Pull</td>
<td>Implies the ability to design and make exactly what the customer wants just when they want it. Don’t make anything until it is needed, then make it quickly.</td>
</tr>
<tr>
<td>Perfection</td>
<td>Perfection implies the complete elimination of waste. Important things to envision is the type of product and operating technologies needed to improve.</td>
</tr>
</tbody>
</table>

It is critical to begin every improvement effort by a thorough specification of product value as defined by the customer (Rother and Shook 2001); the first principle of Lean Thinking (value) thus refers to everything for which a customer is willing to pay (Knuf 2000), i.e. materials, products, parts, or services. However, on a wider scope, the essence of value seems to be the relation between what is produced and what the customer specifically asks for. Consequently, value generation should be conceived in terms of producer as well as customer purposes (Haque and James-Moore 2004). The second principle of Lean Thinking (Value stream) prompts the producer to actively look at what resources (materials, machinery, workforce, information, etc.) are available, and what resources are required for production, i.e. a holistic view of the whole production system rather than a focus on individual specific activities (Rother and Shook 2001).

As such, the value stream is a flow of materials (and/or information) with the goal of weeding out avoidable wasteful activities. The third principle (Flow) is based on the understanding that tasks can almost always be accomplished much more efficiently and accurately when the product is worked on continuously from raw material to finished good. Things generally work better when the focus is on the product and its needs so that all activities needed to design, order, and provide a product occur in continuous flow (Womack and Jones 2003, p.22). This is generally accomplished by the removal of all activities that does not provide any value to the product so that work can progress continually and without interruption; refer to Liker and Lamb (2002) for more information on the seven wastes of manufacturing (overproduction, producing defective products, inventories, motion, processing, transportation, and waiting).

To achieve flow, Lean Thinking relies on its fourth principle (Pull as opposite to push) which tells the producer that any form of production not specifically ordered by a customer is waste (overproduction). Pull thus refers to the ability to design, schedule, and make exactly what the customer wants just when they want it - don’t make anything until it is needed; then make it very quickly (Womack and Jones 2003, p.71). Consequently, if
there is no demand for a product or service then no action should be taken. Specifically for manufacturing processes, pull refers to the authorization of production as inventory is consumed (Hopp and Spearman 2001, p.340); a useful way to think about the distinction between push and pull systems is that push systems are inherently make-to-order while pull systems are make-to-stock.

Continually striving towards producing precisely what the customer wants and delivering the product when expected while eliminating waste is the fifth Lean Thinking principle of **Perfection**, where well developed teamwork through ‘transparency’ (the ability for everyone to see everything) is a key characteristic (Womack and Jones 2003, p.26). Perfection is viewed as an ultimate goal, e.g. the complete elimination of waste (Wood 2004), a goal continuously strived for but a goal that can never be fully achieved – compete against perfection by identifying all activities that are waste and eliminating them (Womack and Jones 2003, p.48). Rother and Shook (2001) proposes the identification of a future improved state for the production system which is worked towards. When this improved state is reached then a new improved future state for the production system is identified which in turn is worked towards spurring continuous improvements.

‘Perfection is like infinity. Trying to envision it (and get there) is actually impossible, but the effort to do so provides inspiration and direction essential to making progress along the path’ (Womack and Jones 2003, p.94).

Thinking Lean implies a firm definition of what is of value to the customer and then to follow this value all the way through the production system so that waste and unnecessary actions are eliminated and all steps that create value are linked in a continuous sequence, steps which in turn are continuously improved so that customer value is enhanced.

### 2.4 Lean Construction

‘…most buyers would like to get exactly the building they need as quickly as possible at the lowest price. […] The same [Lean Thinking] concepts could be applied to construction in general. That it’s possible is not a question. The real question is who will rationalize the value stream and when’ (Womack and Jones 2003, p.292).

Production in construction is currently based on thinking from both craft (traditional construction practices) and mass production (mainly prefabrication) representing a similar situation as when the Lean philosophy was born in manufacturing. Therefore, it seems like the essence of the Lean philosophy should be suitable for construction as well. However, it should be noted that Lean Production was developed from and for the manufacturing industry and therefore its direct applicability to construction should be questioned. Koskela (2000, pp.144-) presents a number of peculiarities of construction, i.e. how the value delivery process of construction differs from that of manufacturing. Understanding this difference is vital in the process of applying thinking from one industry on another.
2.4.1 Construction value delivery

'Construction is a complex production of a one-of-a-kind product undertaken at the delivery point by cooperation within a multi-skilled ad-hoc team' (Bertelsen and Koskela 2004).

Value for manufacturing firms is generally defined by the goods being manufactured such as a car, an engine, or a seat. In this regard, value definition by products is not unique for construction, e.g. a house, a shear wall, or a window. However, the way value is delivered in construction is different from most of the manufacturing industry. Compared to most manufactured goods, buildings are large, immobile one-of-a-kind products mainly site-built where the place of assembly often is different from the place of component manufacturing (see e.g. Gann 1996, Crowley 1998, Bertelsen and Koskela 2004). For the past century, construction products (such as a house or a bridge) have been delivered through temporary production systems (Bertelsen and Emmitt 2005) involving large and loosely tied together project organizations which includes many participants who often have different goals and agendas (see e.g. Sacks 2004, Sardén 2005).

The project organisation is considered a fundamental part of construction; it is a natural way of doing business and delivering value (Ballard and Howell 2003, Koskela and Ballard 2006, Winch 2006). However, Winch (2006) note that the project organization does not have to be the best way of value delivery for all forms of construction; for example, repetitive operations (housing, shear walls, etc.) are not appropriately organized in project mode. Koskela and Ballard (2006) argues that project management, in its current form and understanding, is a possible cause for the issues of construction due to a neglect of the management of production with consequences such as poor control (low reliability) in handoffs and a tendency to promote adversarial relationships. Gabriel (1997) states:

'It is paradoxical that a project is itself a process of continuous change, but within the project every change is hazardous. All change is bad for the client and bad for project performance'.

Due to the uncertainty associated with change in large project organizations, the discussion of complexity in construction has become an accepted theoretical advance. Bertelsen and Emmitt (2005) even goes as far as to argue that the prevailing understanding of construction as an ordered process is completely wrong and that this misinterpretation may be the root-cause of the problems construction management meets over and over again in practice. The complexity discussion in construction seems to indicate that the nature of construction is beyond understanding and therefore beyond management, a research trend opposed by Kenley (2005). In Paper IV it was hypothesized that a cause for the complexity discussion in construction is the inability to accurately define value. Support for this hypothesis can be deduced from Winch (2006) who notes that there is remarkably little research on how buildings add value to clients. Also, Bertelsen (2004) claimed that the concept of creating value has to date mainly focused on value engineering – methods to ensure that the value specified will be delivered to the clients; see Thomson et al. (2006) for an example of such a method.
2.4.2 The development of Lean Construction

‘Lean Construction is a new paradigm challenging traditional thinking about construction and project management’ (Ballard and Howell 2004).

Even though the principles of Lean Thinking were developed from the manufacturing industry, whose form of production differs from that of construction, the message is clear; to become Lean then focus on customer value and never let it out of your sight as the value stream is transformed so that non-value adding activities can be removed. Ever since the introduction of Lean for construction (Koskela 1992), work in both academia and practice has strived to evolve construction and make it better in every way. Based on Lean Production, Koskela (1992) developed 11 principles of flow process design and improvement for construction (Table 2.3). Even up to date, these principles are used in academic Lean Construction literature (see e.g. Farrar et al. 2004, Low and Teo 2005). There is a similarity between these ‘Lean Construction principles’ and Lean Production, see e.g. the 14 principles of ‘Toyota Way’ (Chapter 2.2).

Table 2.3 The 11 principles of flow process design and improvement (Koskela 1992).

<table>
<thead>
<tr>
<th>FLOW PROCESS DESIGN PRINCIPLES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Reduce the share of non value-adding activities.</td>
</tr>
<tr>
<td>2. Increase output value through systematic consideration of customer requirements.</td>
</tr>
<tr>
<td>3. Reduce variability.</td>
</tr>
<tr>
<td>4. Reduce cycle times.</td>
</tr>
<tr>
<td>5. Simplify by minimizing the number of steps, parts and linkages.</td>
</tr>
<tr>
<td>6. Increase output flexibility.</td>
</tr>
<tr>
<td>7. Increase process transparency.</td>
</tr>
<tr>
<td>8. Focus control on the complete process.</td>
</tr>
<tr>
<td>9. Build continuous improvement into the process.</td>
</tr>
<tr>
<td>10. Balance flow improvement with conversion improvement.</td>
</tr>
</tbody>
</table>

Bertelsen and Koskela (2004) argue that the principles of Lean Thinking (Table 2.2) seem to be derived from an ordered situation with a well known product and customer base, a production process that is precisely defined and a well established supply chain – a situation which is closer to manufacturing than construction. Therefore, Koskela (2004a) argued that the principles of Lean Thinking are limited to the transformation of mass production and not suitable for the peculiarities of production in construction. Koskela (2000) even goes as far as to argue that these principles are mere slogans which only deal
with the flow of work in production. Therefore it is argued that construction should move beyond Lean Thinking for a production theory of its own (see e.g. Bertelsen and Koskela 2004, Koskela 2004a). Even if not directly criticizing the authors, Green and May (2005) point out the irony in moving beyond the Lean philosophy before anybody has quite been able to define what it is.

To come to grips with the lacks of the Lean philosophy for construction, Koskela (2000) proposed the Transformation–Flow–Value (TFV) theory of production (Table 2.4) which, according to Winch (2006), allows the principles of Lean Thinking to be applied to the management of construction. According to Koskela (2000), production is performed using transformations of inputs into outputs where materials (and information) flow through value and non-value adding activities with value for the customer as the end goal. Since its introduction, the TFV-theory of production has become the dominant framework for conducting Lean Construction research (see e.g. Ballard et al. 2001, Bertelsen 2002, Bertelsen and Koskela 2002, Freire and Alarcón 2002, Rischmoller et al. 2006).

Table 2.4 The TFV theory of production (Koskela 2000).

<table>
<thead>
<tr>
<th>Transformation view</th>
<th>Flow view</th>
<th>Value view</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conceptualization of production</td>
<td>As a transformation of inputs into outputs</td>
<td>As a flow of material, composed of transformation, inspection, moving and waiting</td>
</tr>
<tr>
<td>Main principles</td>
<td>Getting production realized efficiently</td>
<td>Elimination of waste (non-value-adding activities)</td>
</tr>
<tr>
<td>Methods and practices (examples)</td>
<td>Work breakdown structure, MRP, Organizational Responsibility Chart</td>
<td>Continuous flow, pull production control, continuous improvement</td>
</tr>
<tr>
<td>Practical contribution</td>
<td>Taking care of what has to be done</td>
<td>Taking care that what is unnecessary is done as little as possible</td>
</tr>
<tr>
<td>Suggested name for practical application</td>
<td>Task management</td>
<td>Flow management</td>
</tr>
</tbody>
</table>

The development of Lean Construction is based on construction as primarily project management (see Chapter 2.4.1). The main thrust in Lean Construction for the management of construction projects is the Lean Project Delivery System (LPDS) (Ballard and Howell 2003). In contrast to the traditional view of the construction process as
composed of independent phases, the LPDS understands the construction phases as interrelated, Figure 2.3. The LPDS seems well rooted in the Lean Production system; the Project definition phase of the LPDS has a similar role as the Distribution phase of Lean Production (Figure 2.2), i.e. thoroughly define what is to be produced by accurately understanding customer requirements and translating these into product specifications (Freire and Alarcón 2002). Similarly, Lean Design has the same aim as Product Development in Lean Production (Figure 2.2), i.e. to provide the product with characteristics that fulfil customer requirements.

Figure 2.3 The Lean Project Delivery system (based on Ballard and Howell 2003).

Based on the development of Lean Construction theory as described above, two main views emerge which are summarized in Figure 2.4. The first view (1) represents construction as manufacturing which purpose is to extend Lean Production practices to construction through the principles of flow process design (Table 2.3). The LPDS can be considered to represent a fresh (Lean) perspective on the construction process influenced by this view. The second view (2) represents Lean thinking in construction which purpose is to extend the principles of Lean Thinking to construction through the TFV theory of production (Table 2.4). Both these views have spurred the development of Lean applications for the construction industry.

Figure 2.4 The two dominant understandings of Lean Construction research and development.
2.4.3 Applications of Lean Construction

‘...the more we research in the field we term Lean Construction, the more we reveal of the breadth and complexity of the ways in which construction projects function’ (Sacks and Bertelsen 2006 – from the editorial of the 2006 IGLC proceedings).

The scope of Lean Construction research and development is extensive. Based on a literature survey of Lean Construction theory and applications, Diekmann et al. (2003) identified a total of 16 Lean Construction principles divided into five main areas; 1) Standardization, 2) Culture/People, 3) Continuous Improvement/Built-in quality, 4) Eliminate waste, and 5) Customer focus. Obviously it is impossible to provide with a complete overview of Lean Construction. Instead this section will identify and present the most common applications of Lean Construction. The development of applications for Lean Construction seems to follow the main phases of the LPDS (Figure 2.3).

In Table 2.5, common applications for Lean Construction are presented (see also Papers IV and V). These applications are obtained from an overview of the proceedings from the Lean Construction conference for the past five years (IGLC 2006); the numbers indicates in how many papers the method under consideration was evaluated. In Lean Construction literature, the Last Planner System (LPS) is the most commonly referred to application evaluated in 30% of the published papers (Table 2.5). According to Ballard (2000), the LPS is a philosophy containing rules, procedures, and a set of tools to control the flow of work between trades. If correctly applied, the LPS enable improved flow of production and characteristics of pull through weekly work plans (Ballard 2000). The LPS contains a metric called Percent Plan Completed (PPC) which in Lean literature often is used to measure the performance of production (IGLC 2006). Consequently, following up failures of work execution is a key characteristic of Lean Construction applications.

Table 2.5 Applications of Lean Construction in the proceedings from the Lean Construction conference for the past five years (IGLC 2006).

<table>
<thead>
<tr>
<th>APPLIED METHODS</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
</tr>
</thead>
<tbody>
<tr>
<td>Last Planner System (Lean assembly)</td>
<td>7</td>
<td>7</td>
<td>6</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>Value stream mapping (Lean supply)</td>
<td>2</td>
<td>4</td>
<td>7</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Line of Balance (Lean assembly)</td>
<td>2</td>
<td>1</td>
<td>5</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>3D/4D modelling (Lean design/assembly)</td>
<td>1</td>
<td>2</td>
<td>-</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Partnering (Project definition)</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Concurrent Engineering (Lean design)</td>
<td>2</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>Target/Kaizen costing (Project definition)</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

Evaluated in 25% of the published papers (Table 2.5), another common application for Lean Construction is value stream mapping (see e.g. Arbulu and Tommelein 2002 for an
Koskela (2004a) refers to the value stream as a flow of materials (and/or information) with the goal of weeding out avoidable wasteful activities. In this regard, new scheduling techniques striving to better plan and control events during site production, such as Line of Balance (evaluated in 15% of the papers) and 3D/4D modelling (evaluated in 10% the papers), has become important additions to Lean Construction theory. According to Heinrich et al. (2005), control of activities, trades, and resources on the construction site is of vital importance for the management of site production in construction. Jongeling et al. (2005) argued that construction planners need to carefully design a process that ensures a continuous and reliable flow of resources through different locations in a project, i.e. improve the control of production by reducing its variety.

The importance of learning to see work flow in construction was pointed out by Ballard et al. (2003) who stated that making work flow smoothly and reliably is the first step in performance improvement at every level in the production system. Currently there is a development effort attempting to establish a flow physics of construction itself (Bertelsen et al. 2006) which should enable existing production systems to be improved and new effective ones to be designed. The methods developed and accepted for Lean Construction (e.g. LPS, value stream mapping, Line-of-Balance, and 3D/4D modelling) mainly seem to enable the flow characteristics of the Lean philosophy, i.e. these methods are means of identifying waste so that it can be reduced or completely eliminating. The wastes of construction are generally referred to as the same as those of manufacturing (Chapter 2.3). However, specific wastes of construction have been identified; for example making-do – the starting of a task without proper information being available (Koskela 2004b).

In Figure 2.5, the purpose of Lean Construction applications is exemplified; for example, target costing allows the balancing of customer value with available resources so that what is agreed on can actually be produced, i.e. reduction of variety during design, while the Last Planner System manages the production process so that scheduled production tasks can be accomplished as planned, i.e. reduction of variety in site production. Consequently;

- The main driving force in the development of applications for Lean Construction is production system design for improved control of the production process – stability (reliability) and better control (predictability) are sought through the reduction of variety in work practices and supply chains.

![Figure 2.5](image-url)  
*Schematic illustration of variety reduction through Lean Construction applications.*
2.5 Theory discussion; Lean thinking in construction

Even though Lean Construction has been under development for 15 years now there seems, quite surprisingly, to be no commonly accepted view of what it means to be ‘lean’ – not even in Howell’s (1999) paper ‘what is Lean Construction’ is a clear definition given. A critique also voiced by Green and May (2005) who argue that any empirical research into the way ‘leaness’ is diffused into practice is missing within Lean Construction. Considering the many development efforts and application of Lean Construction up to date, Ballard and Howell’s (2004) view on Lean Construction as a new paradigm challenging traditional thinking about construction and project management seems to best define what the Lean philosophy should imply for construction. This is a vague definition which does not provide any clear guidance for Lean Construction research. However, a narrow definition of Lean Construction could, in a worst case scenario, obstruct future development initiatives by concentrating research to areas which are no longer relevant for the development of construction or not suitable for specific types of construction settings.

The Swedish industrialization trend in multi-storey timber housing construction seems to represent such a construction setting (Chapter 1.3). What does it imply to work with Lean Construction? The principles of Lean Thinking (Table 2.2) are the drivers of both the development of Lean Construction theory (Chapter 2.4.2) and its applications (Chapter 2.4.3). These principles describe the most important aspects of how to think in the delivery of customer value so that profitability is generated. Consequently, knowledge of industry practices associated to the five Lean Thinking principles is required to understand how the Lean philosophy can be applied for construction. To aid in this understanding, a conceptualization of the Lean Thinking principles in a production setting, such as multi-storey housing construction, has been developed (Table 2.6). This framework represents a summary of the Lean philosophy (Chapters 2.1 to 2.4) associated to Value, Value Stream, Flow, Pull and Perfection which can be used to provide a Lean Construction perspective on contemporary Swedish multi-storey timber housing construction.

The most important aspect of the Lean philosophy is the value concept which originates from the customer and influences work in every stage of production (Table 2.6). Therefore knowledge of the customer (1a) and what the customer values (1b) are important. Also, it is important to understand what is of value for the delivery team (1c) and how this value is specified in the products being produced (1d). For a comprehensive understanding of a production system it is necessary to clarify (2a, 2b) and standardize current practice (2c). In this regard, knowledge of the supply chain is required (2d). Waste reduction throughout the production system is one of the most pronounced aspects of the Lean philosophy and the principle which is most easy to understand and to tackle in practice. But it is important to identify the root causes of waste (3a) and methods of dealing with waste (not necessarily elimination) as it is observed (3b). To identify waste reduction activities it is important to clearly define what is being done and why, i.e. to locate key performance indicators for the production system (3c) and measures of current practices which provides a foundation for developing future improvements (3d).
The next step in understanding the production system is how the customer can influence what is to be produced (4a, 4b). The facilitation of a non-stock production system able to produce and deliver instantly (an impossible feat by itself but nonetheless an important goal) is dependant on activities for shortening lead and cycle times (4c); what is maybe of more importance is to understand (‘…a conscious effort…’) the effect of lead and cycle times on flow and pull. When work is actually needed, then it is important to define the prerequisites for work so it can be executed (4d). Improvement of the production system relies on everyone involved being able to see and understand how work is performed (5a) so that experiences from all involved personnel can be captured and used (5b). Finally, there should be a conscious effort to continuously improve on the value delivered to the customer (5c) and the value which is generated for involved stakeholders (5d).

A comprehensive understanding of Lean Construction clearly is a complex undertaking with many ways of thinking and proposed applications. However, the foundation for the understanding of the Lean philosophy is the five founding principles of Lean Thinking. Knowledge of their implication for specific production settings (Table 2.6) can provide a deeper understanding of production system design and the efforts required to improve so that customer value can be delivered while value is generated for involved stakeholders.
CHAPTER 3  

Research method

This chapter relates for how the research presented in this thesis has been performed, i.e. research strategy and data collection methods. As such, this chapter provides a starting point in guiding the reader through the contents of the empirical and analysis sections of this thesis.

3.1  

Academic background

My inherited understanding of the design and production of timber structures (Björnfot 2004) has evolved from my background in civil engineering with construction speciality. The main driving force during my research is simplification through standardization – if something is complicated then my belief is that there is a lack of knowledge of the studied phenomena. In this regard, understanding construction through the Lean philosophy fits my view of the world well. The main source of my understanding of timber construction emanates from the research environment in which my research has been performed. Focus of the research group is on three research fields within timber construction; process management, industrialized production and timber engineering. The research group is responsible for education of university students in timber engineering (long-span structures and timber-frame housing) where I have taken part during the previous five years. Fruitful discussions with co-workers and their research (e.g. Bergström 2004, Sardén 2005, and Höök 2005) has influenced and spurred this research project ever onwards.

3.2  

Research strategy

Based on the aim of this research, the empirical section of this thesis is divided into two parts; 1) a study of the contemporary Swedish multi-storey timber housing production process and 2) analysis of these results from a theoretical perspective (Chapters 2.4 and 2.5). The many ways of constructing multi-storey timber housing presents an interesting problem – there is no realistic way to gain knowledge of contemporary practices by covering every type of production method. However, the current development trend in Swedish multi-storey timber housing seem to indicate that more and more components are included in the construction products before assembly, i.e. the degree of prefabrication is increasing. To cover this trend in multi-storey timber housing construction it was decided to study three types of production methods:

1. **Timber element prefabrication** represents a production process with characteristics of both traditional and industrialized construction.

2. **Timber volume prefabrication** represents a highly industrialized production process with historical relation to the Swedish detached housing industry.

3. **Timber volume/element prefabrication** represents an effort at building system development for industrialized construction.
CHAPTER 3  
RESEARCH METHOD

The Lean Project Delivery System (Figure 2.3) illustrates the wide scope of information required to completely analyse the application of the Lean philosophy for construction. This research is limited to activities related to the production process; 1) the product design (not the design process), 2) the manufacturing process (a vital part of industrialized construction), 3) the delivery of products to the construction site (supply), and 4) the on-site assembly process (including finishing). These phases very much affect each other and can therefore not be analysed separately – case study research is a viable research strategy when the boundaries between phenomenon and context are not clearly evident (Yin 1994, p.13). Therefore, knowledge of the production phases in relation to the three production methods is uncovered through case studies. In Figure 3.1, the case studies are related to the theory presented in Chapter 2 and the theory presented in (Björnfot 2004).

![Figure 3.1 Work performed in relation to research timeline.](image)

The empirical part of this thesis is greatly influenced by the results presented in the five appended papers. Paper I contains the condensed results from (Björnfot 2004) where constructability and modularity are used as complementary theories to Lean Construction to better understand the production process (see Chapter 1.2). Results from the first case study were analysed in Paper II. Using further results from case study one, Paper III was written. Results from case studies two and three were published in Paper IV and Paper V. Since the case studies have been conducted while theory has been uncovered, the main research strategy of this research project is theory driven, i.e. theory has constantly been feeding the selection of methods for data collection and its execution. The overall research process is therefore iterative, or investigative - a 'snowball' research strategy according to Miles and Huberman (1994, p.28) which was initiated already in (Björnfot 2004).
3.3 Case study research

Case study research typically uses multiple methods and tools for data collection from a number of entities by a direct observer in a single, natural setting that considers temporal and contextual aspects of the contemporary phenomenon under study (Meredith 1998). To help the researcher there are three general types of case studies; exploratory, descriptive, or explanatory (Yin 1994, p.4). One common concern with case study research is the massive amounts of information generated which can be difficult to structure and analyze (Yin 1994, p.10). Therefore it is important to properly define the case, i.e. the focus of the research and its boundary (Miles and Huberman 1994, p.25). The unit of analysis for all three case studies is the construction components utilized which provides with information regarding the product design, manufacturing, and assembly processes. The boundary (context) of each case study is outlined below.

**Case study 1** (Table 3.1) investigates the contemporary practices of manufacturing, delivery, and assembly of one multi-storey timber housing project – involving a total of five six-storey houses. This is a descriptive case study, i.e. the purpose of the case study is to provide an understanding of contemporary work practices. As such, this study is of qualitative nature where qualitative data are used to provide with a deeper understanding where required, for example the assembly process.

**Case study 2** (Table 3.1) investigates the contemporary practices of volume prefabrication from the perspective of one company. As such, the purpose of the study is descriptive mainly involving qualitative data which is used to describe the volume production system.

**Case study 3** (Table 3.1) investigates one Swedish initiative at industrialized construction of multi-storey timber housing which involves three construction component suppliers and one architect firm. The purpose of the third case study is to provide a deeper understanding of the development effort required to support production system design for industrialized construction. Therefore this case study is exploratory.

<table>
<thead>
<tr>
<th>CASE STUDY 1</th>
<th>CASE STUDY 2</th>
<th>CASE STUDY 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Multi-storey housing project</td>
<td>Timber volume producer</td>
<td>Multi-company endeavour</td>
</tr>
<tr>
<td>(2) Descriptive</td>
<td>Descriptive</td>
<td>Exploratory</td>
</tr>
<tr>
<td>(3) Timber elements</td>
<td>Timber volumes</td>
<td>Timber elements/volumes</td>
</tr>
<tr>
<td>(5) 2005-02 to 2005-12</td>
<td>2006-03 to 2006-10</td>
<td>2005-04 to 2006-10</td>
</tr>
</tbody>
</table>
Each of the three cases contains a single holistic case study (Yin 1994, p.39) – holistic since the aim is to study all production phases from the point of view of specific units of analysis. The rationale for the single case designs is on revelatory basis, i.e. a situation where the researcher has the opportunity to observe and analyze a case previously inaccessible to scientific investigation (Yin 1994, p.40) – refer to Chapter 3.5 for a discussion on the quality and risks of conducting single case study research. Obviously the multi-storey timber housing project considered in case study one is not the only multi-storey timber housing project available for study. However, the opportunity for in-depth study from many different perspectives (see Chapter 3.4) provided a unique opportunity for data collection; the same project was also studied in-depth by Sardén (2005) but from a strategic and relational point of view. Case study three provides with a good opportunity for in-depth study due to continuous cooperation with two of the involved companies; one is involved in case study one and one company is the focus of case study two.

3.4 Data collection methods

The production system of the volume producer in Case study 2 has already been extensively studied in a number of sources (see Bergström 2004, Olofsson et al. 2004b, Höök 2005, Höök 2006). Therefore, relevant empirical data for this case is collected through a literature survey of these sources. The research presented in this literature has been performed at my research group which has allowed for discussions and a deeper understanding of the presented results. Specific data collected for this case study includes knowledge of the volume building system, the supply chain, and the manufacturing and assembly processes. Data collection for case study two is not covered further in this text.

Data collection for Case study 1 covers an understanding of the manufacturing process, logistics (supply) and site assembly phases (including interior finishing) of the construction process. What is also of interest is to understand how the design of the timber elements affects the production process. The main methods of data collection (Table 3.2) for case study one are reviews of design documentation and site observations from manufacturing and assembly. These methods are mainly supported by interviews with representatives from suppliers, contractors, and production personnel. Additional information was collected from design meetings and discussions with other involved researchers.

During case study one, a project group was formed with the purpose of collecting experience from the construction project and to present this information for all involved participants. The case study results and analysis presented in Björnfot (2005) – ‘Conditions for industrialized construction’ – was part of the work performed and presented by the project group. The experience of the project group members included the construction research community as well as participants with practical construction experience. As a group, interview sessions were held with critical participants from the construction project (Table 3.2); specifically the contractor site management, and the manufacturer of the timber floor and wall elements who was also responsible for structural assembly.
Table 3.2  Summary of data collection methods used for Case study 1 and 3. (1) Interviews, (2) Design meetings, (3) Project meetings, (4) Observations, (5) Documentation.

<table>
<thead>
<tr>
<th>Case study 1</th>
<th>Case study 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Designer at manufacturer (one interview) Manufacturer factory manager (one interview) Contractor site personnel (see Appendix A)</td>
<td>Open interviews with volume and manufacturer personnel at business and conceptual design meetings.</td>
</tr>
<tr>
<td>(2) Detailed design meetings (3 times)</td>
<td>Business group meetings (5 times) Conceptual design meetings (2 times)</td>
</tr>
<tr>
<td>(3) One interview session with the contractor One interview session with the manufacturer Seminar with presentation of project results</td>
<td>Not applicable</td>
</tr>
<tr>
<td>(4) The manufacturing process (site visits) The on-site assembly process (web camera) Structural and interior finishing work (site visit)</td>
<td>Not applicable</td>
</tr>
<tr>
<td>(5) Design documentation / drawings Manufacturing documentation / drawings Protocols from design meetings Protocols from construction site meeting Reports from the project group work Case study results (Sardén 2005)</td>
<td>Design documentation / drawings Protocols from design meetings Protocols from business group meetings Case study results (Höök 2005) Case study results (Bergström 2004)</td>
</tr>
</tbody>
</table>

The interviewees expressed a common interest in providing the project group with information and to solve the observed problems which meant that much information was accessible by the project group. The work by the project group was presented during a seminar which provided with in-depth discussions and critical assessments of obtained results. During the case study, the on-site production process was observed through a web-camera which enabled continuous detailed study of the assembly process. During this study, important activities from the logistics and assembly phases were noted down which enabled measurement and analysis of assembly cycles and assembly times. The project sessions together with the observations and interviews provided information regarding the mapping and analysis of the manufacturing, assembly, structural-, and interior finishing processes which in turn enabled a comprehensive understanding of the events taking place.

Data collection for Case study 3 (Table 3.2) covers a new initiative at industrialized construction where new construction components are designed. Since the initiative has not been seen in practice yet, the case study only covers the conceptual design phase, i.e. the design of the building system and supporting improvements as well as ideas from the design team relating to the management of logistics and assembly. Therefore, the available sources of information for this project are limited to documentation detailing the concept which has been supported with open ended interviews with involved personnel during
design meetings. No input from practice is available since the first project is planned during spring 2007. However, the integrated structural system is by no means untested since the system is based on the timber elements manufactured by the manufacturer involved in case study one, and the timber volumes are manufactured by the producer studied in case study two. Consequently, results from case studies one and two are used to support the results presented in case study three.

3.5 Research quality

According to Yin (1994, p.32-33) four tests are commonly used to establish the quality of any empirical research; 1) Construct validity, 2) Internal validity (only concerns explanatory case studies), 3) External validity and 4) Reliability. A tactic to increase construct validity is by using multiple sources of evidence. In this regard, data collection for the case studies is validated through observations, review of design documentation, interviews, and related work by other researchers at my research group and elsewhere (Table 3.2). Another tactic is to have the case study results reviewed by key informants. In this regard the results from the first case study are further validated through the project meetings and the seminar (Chapter 3.4).

External validity concerns the problem of generalizing the results which is viewed as one of the major barriers of case study research (Yin 1994, p.36). Since all three case studies are composed of a single case study (i.e. one project, one company and one company cooperation) the question of possible generalization to Swedish multi-storey housing construction in general and on an international level is important from a methodological viewpoint. Especially the results from case study three is worthy of a deeper discussion on generalization since these results are partly based on ideas and wishes of the design team. Based on the actual results obtained (Chapter 4) and their analysis (Chapter 5), Chapter 6 presents a discussion on the possibility of generalizing the results obtained.

Finally, reliability has the objective of making sure that if a later investigator followed exactly the same procedures as described and conducted the same case study then the later investigator should arrive at the same findings and come to the same conclusions (Yin 1994, p.36). The operations conducted in the case studies have been explained in detail above which should allow another researcher to follow the same steps using the same data collection methods to obtain comparable results to those achieved (Chapter 4). However, as the specifics (work methods, planning, etc.) of production in construction are ever changing between projects (depending on the client’s wishes, involved participants, and experience feedback from completed projects) it is likely that the obtained results will differ. Therefore, two projects with similar characteristics are difficult to find. With input from the obtained results (Chapter 4) and the performed analysis (Chapter 5), this discussion on reliability is continued in Chapter 6.
Chapter 4 presents case study results from element, volume and volume/element prefabrication which provide a basis for an understanding of contemporary Swedish construction practices. The results presented contain information from the design, manufacturing, logistics, and assembly phases.

4.1 Case study 1 – Element prefabrication

This case study concerns the application of prefabricated floor and wall elements in a multi-storey timber housing project which involves five buildings of six floors each for a total of 95 apartments over 8,600 m² (the exterior and interior layouts are presented in Paper III, Figure 2). Case study results are presented in Paper II, Paper III, Paper IV and Paper IV as well as in Sardén (2005) – see also Björnåt (2005) for a comprehensive description and analysis of the industrialized construction process. The scope of the case study results presented here concerns the manufacturing, delivery, and on-site assembly (including finishing work) phases according to Paper II, Figure 1. Results from the design phase are not explicitly presented other than in relation to the above phases.

The timber element manufacturer who was responsible for the manufacturing, delivery and assembly of the timber elements is one of northern Sweden’s largest sawmills and one of Europe’s leading and most modern glulam producers. During the case study it was, by the project group (Chapter 3.4), concluded that the most important component, and the component with the most possibility of future development, was the floor element, mainly because of its importance for the structural function of the whole building and the large amount of integrated installations. Therefore, the results presented from the case study mainly concern, but is not limited to, the floor elements since knowledge of involved components is required to fully understand the whole production process.

The floor element (refer to Paper II, Figure 5) consists of a load-carrying system (massive timber slabs and T-joists), flooring (the slabs are used as finished floor surface), sub-ceiling (consisting of a three layer cross-work of timber beams, insulation, and two layers of plasterboards), and installations (piping for ventilation, water, and drains). All of the above components, except for the last cross-work of timber beams, the insulation in the sub-ceiling, and the two layers of plasterboards were integrated already in manufacturing.

4.1.1 Manufacturing and delivery

In Paper II (Figure 6), the manufacturing process was presented in a flow chart and each activity was in detail described in Paper II (Table 1). The main observations from the process mapping were the way work was performed and its implications on the construction process. During manufacturing, a high degree of automation was used. The
manufacturing process is very much based on the glulam manufacturing process which has been used and continuously developed for many years by the manufacturer. Even using an automated manufacturing process (using an automated CNC machine), elements were, in some cases, delivered to the construction site with wrong dimension. A cause for this issue was identified as poor design documentation (Paper II, Table 2). To solve this issue, more attention was given to the manufacturing process, especially tolerance issues emanating from the detailed design stage, which helped reduce the amount of additional work on the construction site manually spent cutting or re-ordering elements due to size issues.

During manufacturing, a large amount of traditional construction work was performed inside the factory. Actually, the majority of work during manufacturing was performed using hand-held machinery while only a minor part of the manufacturing process was automated. In Paper II (Table 2) it was argued that handwork using standard handheld machinery is prone to human errors and mistakes, which was especially evident in complementary site work. As a solution to this issue, on-site installation subcontractors were in close contact with factory installation workers and the manufacturer factory supervisor which, according to the production personnel, resulted in a reduced amount of site work spent correcting installation placements. As a consequence, the time spent adding insulation or plasterboards to cover up the corrections were reduced.

The manufacturer was also responsible for the delivery of floor elements to the construction site. Guided by the assembly schedule, the elements were supplied in two batches per floor, ‘just-in-time’, using one truck and trailer (Appendix B). The delivery was carefully organised in the detailed design phase to minimize the amount of transportations. It was actually stated that the height of the elements was a limiting factor in design so that delivery could be optimized. Due to the limit in height, the sub-ceiling could not be integrated to the elements at the factory which was an aim of the design team – a decision which eventually led to many problems on the construction site (see Chapter 4.1.2).

On the construction site, the assembly process was supervised by four workers and a tower crane; two workers connected the elements on the truck while the remaining performed assembly (refer to Appendix B for more information). A general consensus among all involved parties was that delivery and off-loading was working as intended. However, the straps (Paper II, Table 1) used to off-load the elements caused additional on-site work since they had to be removed and the remaining holes had to be carefully insulated to cover the strict building regulations on sound and fire insulation.

4.1.2 Assembly and finishing work

The on-site production process was performed in two stages; assembly of the load-bearing structure, and structural and internal finishing work. In the first stage the load-bearing structure was assembled using the prefabricated wall and floor elements. This work was performed in a nine day assembly cycle for each floor (Table 4.1). With the floor structure
assembled, complementary work on the sub-ceiling was performed; adding the third layer of timber to the sub-ceiling cross-work, followed by electricity and the sprinkler system. Finally, missing insulation and plasterboards were added (refer to Paper III, Figure 6 and Appendix B for an overview of activities). Since timber is susceptible to weather, a “dry construction” process was aimed at through the use of a covering tent (Appendix B).

Table 4.1  
The assembly process (as observed using the web-camera) and finishing work (obtained from the production schedule) for each floor.

<table>
<thead>
<tr>
<th>DAY</th>
<th>ACTIVITY</th>
<th># OF DAYS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Placement of wall linings in preparation for wall assembly</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>Assembly of outer wall elements</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>Assembly of load-bearing inner wall elements</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>Assembly of floor elements over gable apartments</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>Assembly of floor elements over central apartment</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>(Assembly of floor elements over common space area)</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>Finishing work on sub-ceilings</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Finishing work on installations</td>
<td>≈ 16</td>
</tr>
<tr>
<td></td>
<td>Adding plasterboards to sub-ceilings and outer walls</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Adding plasterboards to inner walls and bathrooms</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Painting of walls</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Finish floor (polish and sealing)</td>
<td>7</td>
</tr>
</tbody>
</table>

At the beginning of the project (house 1 in Paper II, Figure 3), the know-how of the element system was mainly in the hand of the manufacturer’s personnel while the contractor work crew were unfamiliar working with the timber elements. Therefore, the manufacturer factory supervisor was initially forced to spend time teaching the work crew how to handle the new system. The supervisor spent a total of six weeks (three assembly cycles) on site transferring his knowledge to the work crew. This enabled feedback of notches, tolerances, connectors, etc. to be brought back directly to manufacturing. All construction site personnel agreed that the manufacturer factory supervisor’s role was crucial for the success of the project. In Paper II, Figure 11 the participants roles during the production phase are identified and illustrated.

However, even with improved communications the variability in assembly time was significant, ranging from about ten minutes up to an hour per element (Björnfot 2005). The main cause was identified as incorrect element dimensions and tolerances due to errors in design and manufacturing. These errors resulted in rework on site, e.g. a complete waste of resources. Even though the assembly of the floor elements for each
floor was generally performed over a two day cycle (Paper III), a three day span (Table 4.1) was given to account for the large variance in assembly time. Despite the tolerance problems, the assembly of the load-bearing structure was considered to be productive and efficient by most involved participants. However, structural and internal finishing work was still considered problematic due to a large number and range of different fasteners (Paper II) and deficient site organization and production planning (Paper III).

4.1.3 Concluding remarks

Due to the material (timber) and the element system being relatively fresh on the Swedish construction market, the structural system was procured with a fixed price design-build contract where the contractor was promised full responsibility for design and assembly even though this was the first time this particular system was used in practice – “the manufacturer advertised an undeveloped product, not ready for use in a construction project. They were in belief they were contracted as suppliers only, when they had clearly been contracted with overall responsibility for their products (manufacturing to assembly).” As a result, the system was continuously developed during the project resulting in waste due to rework and delays. This situation was not acceptable to the contractor who, rightfully, was expecting a fully developed system which eventually led to claims on the manufacturer during production and after project completion. However, even with the experienced problems, the project was completed on time and the client was satisfied with the value delivered.

4.2 Case study 2 – Volume prefabrication

This case study concerns a producer of prefabricated volumes (Paper IV, Figure 2) for the Swedish multi-storey housing market. The results presented are obtained from a literature survey of previous case study research performed at my research division, e.g. Bergström (2004), Olofsson et al. (2004b), Höök (2005), and Höök (2006). The company runs everything in-house, i.e. they procure land, they design the building according to customer demands, they produce prefabricated volumes in their factories, and they assemble and finish them on the construction site. The volumes are produced in a standardized manufacturing process where wall and floor elements are assembled to three-dimensional volumes. Before being delivered to the construction site, the volumes are finished with installations, façade, interior surfaces and finishing to create ready-to-use living space; see further Bergström (2004, p. 14-15) and Höök (2005, p.39-42).

4.2.1 Tendering and design

The case company prefer to, and most often, offer their standardized volume system to landlords. Through the standardized product, the company is able to utilize a “simplified”
CHAPTER 4  CASE STUDY RESULTS

tendering process which involves the adaptation of the house layouts to the project in question, negotiation of price and date of delivery, and setting up a list of options for the clients’ tenants. Only minor changes of the principle design (interior and façade design, and add-ons such as balconies) are allowed to keep a high production-to-cost efficiency. When the contract has been signed, the client initiates the sales and customization process of the houses. When 30% of the apartments are sold, the start order is given for detailed design to commence. From the detailed design phase, design drawings are delivered to the manufacturing process. When production starts, information of selected customer options from the customization process is passed to the case company in order to individually customize the tenant-owned purchased apartments (Olofsson et al. 2004b).

4.2.2  The production system

Volumes are produced by first manufacturing elements (walls, floors, etc.) which are then assembled to three-dimensional volumes inside the factory. The manufacturing process uses automation in conjunction with traditional construction work to produce volumes in a cost-efficient manner with short lead times. In manufacturing the case company utilize local sub-contractors under long-term contracts who are brought in-house to perform work; refer to Bergström (2004) and Höök (2005) for in-depth write-ups. After manufacture, the volumes are transported to the construction site, where they are assembled and remaining fixed equipment is added. The standardized design of the product offer leads to a standardized delivery of the volumes to the construction site, using trucks and trailers. In this manner, the company is able to produce and deliver volumes for projects all over Sweden (a large country considering distances).

Before the volumes are delivered, the foundation has already been constructed while work on the roof has started (commonly composed of prefabricated rafters from local producers) leaving only assembly of the volumes, a task which is performed straight from the trailers using one tower-crane and a local workforce often with long relations to the company. Therefore the process of assembling a normal sized building is quick, usually about one days work. When the volumes are assembled, the process of finishing installations and remaining interior commences. Due to the standardized design of the volumes and the long-term contracted assembly crews, the finishing process is straightforward and often performed with a minimum amount of wasted effort.

4.2.3  Concluding remarks

The company is very much focused on providing their customers with what they want (within the limitations set by their manufacturing process) while keeping the design and production processes as simple as possible. One reason this is possible is that the company own the majority of the value stream by themselves, e.g. they bring subcontractors for installations in-house and uphold long-term relationships with important suppliers and
assembly crews. Even though it seems like the company is strict in keeping to its volume production system, they are in reality keen on meeting customer requirements – the company has a limited possibility of delivering “old-fashion construction flexibility” where everything is possible. Even though client involvement is only possible within the rules set by the production system, which may seem like a severe limitation in meeting customer demands, the customers generally know what to expect from the company product and how much involvement they are allowed in design.

4.3 Case study 3 – Volume/Element prefabrication

Case study three concerns a new initiative on the Swedish construction market where the element producer in case study one (Chapter 4.1) has joined forces with the timber volume producer in case study two (Chapter 4.2), an architect firm, and a roof systems supplier. During a three year period these companies has worked together to develop a new product. The goal of the development effort is to increase their market shares, i.e. to produce cheaper houses with a larger flexibility to a larger market than they can do by themselves. Case study results are presented in Paper IV and Paper V.

4.3.1 Design development

Early it was decided that the competitive edge of the system, over other systems, was to offer a “complete package” (design, manufacturing, assembly, etc.) in a cost and time efficient industrialized construction process involving the main products from each of the involved companies. The main customers for the system were identified as landlords who offer flats to tenants at a price of around 1,100 to 1,200 Skr/m² (≈ 110 €/m²) in multiple floors. Common flats were identified as 55 m² in size with a total production cost per apartment of 700,000 Skr (≈ 70,000 €), including cost for land and connection. Based on these numbers, the total cost per apartment was calculated to 12,700 Skr/m² (≈ 1,300 €/m²) which should be compared to about 17,500 Skr/m² (≈ 1,700 €/m²) per flat in contemporary multi-storey housing construction (almost a 30% reduction).

For the development of the product, it was decided on a target production cost of 8,000 Skr/m² (≈ 800 €/m²). A concept building featuring a four storey apartment building was used to develop a standardized building system (Chapter 4.3.2). Relational contracting was employed between the involved suppliers so that future customers are met with one delivery team instead of a multitude of independent manufacturers and subcontractors. Through the contractual regulation and the standardized product, the involved companies are able to utilize a simplified tendering process similar to the practice already used by the volume producer (Chapter 4.2.1). The increased flexibility of the product offer should enable clients to become further involved in the design process without compromising the stability and continuity of the suppliers’ current manufacturing processes.
4.3.2 The developed ‘product’

It was early on decided that the products already manufactured by the involved producers - prefabricated timber elements (Chapter 4.1) and volumes (Chapter 4.2) - would be the foundation of the developed product (see Paper V, Figure 1). The main idea of the initiative was to use the timber volumes and timber elements where they are best suited. In conceptual design of the product offer it was identified that a large and difficult part of site-production is concerned with finishing off “wet areas” such as bathrooms and kitchens. Therefore it was decided to attempt to prefabricate such areas as volumes in order to better control the difficult finishing work on site. It was also decided to include as much as possible of the installations in the volumes since experience from volume prefabrication has shown that site production of installations is a common source of waste and a higher quality can be maintained in factories.

The layout of the houses is based on volumes, but to achieve a higher degree of flexibility than can be accomplished with volumes alone, prefabricated timber elements are used to complement the volumes allowing more flexible layouts – using elements, almost any kind of building can be produced. However, heavy efforts of standardizing the elements (for example, standard wall and floor element designs) have been made to simplify the manufacturing and site assembly processes. This design effort has significantly reduced the number of different types of elements used. Standardization is considered an important aspect in the promotion of a construction process where standard work in manufacturing, delivery, and site assembly can be utilized. Regardless, it was not until late in the design process that standardization became a key characteristic of product development. In the end of the development process a production cost of 9.100 Skr/m² (≈ 900 €/m²) was achieved which was higher than the target cost.

4.3.3 Production system design

The effort to standardize the components included in the product resulted in reduced costs – calculated as cost savings in manufacturing and assembly. This allowed the delivery team to pinpoint key component suppliers and to simplify the supply chain by reducing the number of suppliers, i.e. it was decided on the suppliers who would be able to deliver the required components when needed and at the right price and quality (an internal analysis of potential suppliers was performed by the delivery team). The delivery team has a desire to integrate lower tier component suppliers into their value chains and to engage in long-term win-win relations with suppliers so that stable supply chains can be formed. This allows the delivery team to be in control of the whole supply chain (again similar to the volume manufacturer) and to continuously improve on the product and associated processes together with everyone involved.

The development of the production system is influenced by the manufacturing processes already employed at the manufacturers. A goal is to design an on-site assembly process
with manufacturing characteristics, i.e. use of automation for material handling and movement. Additionally a dry site production process is aimed at through the use of a covering tent (compare with the covering tent utilized in Case study 1). All in all, the construction site becomes much like a factory in which components are shipped in and assembled as they are delivered. Such an assembly process demands attention on logistics for Just-in-Time delivery of components. A few such alternatives for the management of component delivery has been examined by the delivery team, but at this time it is unsure of which model will be used in practice. Working in this fashion, the delivery team believes that it should be possible to assemble one complete floor per week – a four day reduction in assembly time compared to case study one (Table 4.1).

The developed production system is reliant on tight cooperation within the delivery team and with component suppliers, as well as tight control of the supply chain for logistics management. To facilitate cooperation and control of the production system, a computer support system is being developed. The aim of the computer system is to allow for simultaneous sharing of information between the involved suppliers as an aid in the design process, to facilitate short lead times with increased customer involvement, to support the manufacturing processes, and to guide the delivery of components to manufacturing and to the construction site.

4.3.4 Concluding remarks

Through this initiative, the volume producer achieves a higher flexibility in his product offer and is therefore better able to meet new forms of client requirements while still offering a standardized product which is familiar and possible to be produced efficiently. The element producer, whose prefabricated element system is lacking in development and has only really been tested properly on one project, gains an increased share of the housing market and the possibility of developing its product in real applications. Even though it seems like this product development endeavour has all possibilities of success, it will be interesting to see if all ideas are transferable to practice.
Chapter 5 provides a theoretical perspective on the case study results. Based on the understanding of Lean Construction (Chapters 2.4 and 2.5), this chapter analyses the applicability of the Lean philosophy for Swedish multi-storey timber housing construction.

5.1 Introduction and case study categorization

As described in Chapter 3.1, the case study analysis of the obtained results has been conducted while theory has been uncovered. This growing understanding is shown both in the theory section (Chapters 2.4 to 2.5) and in the analysis performed in the appended papers. Paper II and Paper III analyses the work flow of the element case study while the analysis in Paper IV and Paper V analyses all three case studies based on the theoretical framework presented in Table 2.6. The analysis of the case study results presented in this chapter follows the same order, i.e. first an analysis of work flow issues in element prefabrication followed by a more comprehensive theoretical analysis of the production system according to the theoretical framework.

The case study results present the products and work practices by two producers of specific construction products (elements and volumes) for multi-storey housing construction while the third case study describes an initiative combining these two production methods. In Figure 5.1 these methods are related to their degree of prefabrication, i.e. amount of components integrated in the products before delivery to the construction site. These production methods have influenced the execution of production, i.e. element prefabrication requires a large amount of site work while volume prefabrication represents a more manufacturing oriented production system. The main customers for each of the production methods are briefly summarized below (see also Paper IV, Table 2):

- The element producer offers their element system to contractors whose requirements typically are high quality, low lead times and constructability.
- The volume system mainly attracts landlords (offering student dwellings) who are offered a well developed product adaptable according to predetermined guidelines.
- The volume/element initiative allows additional flexibility over the volume system which therefore should attract landlords with more diverse values.

![Figure 5.1](image-url)  
Schematic illustration of the relation between the three production methods.
5.2 A flow perspective on element prefabrication

Even though Swedish multi-storey timber housing construction is increasingly influenced by prefabrication, traditional construction practices still has a strong position in everyday work. The element case study in many ways represents a ‘clash’ between the traditional value delivery process (represented by a large amount of involved stakeholders and a solve-it-on-site mentality) and a new way of thinking in value delivery through prefabricated components (represented by the timber element system). The issues observed (e.g. poor work conditions, rework, delays, etc.) throughout the case study can be associated to this ‘clash’, i.e. an inability to integrate prefabricated components with traditional production practices. From Papers II and III, three core issues for the identified problems emerge;

- **Complicated design decisions** concerns the design of the floor elements and the decision to finish a large part on the construction site resulting in poor work conditions and tolerance issues leading to rework and delays (Paper II). Lack of standardized element sizes led to variety in the output from manufacturing (caused by human errors in design and manufacturing) which in turn led to difficulties in establishing learning throughout the assembly process (see further Paper II).

- **Poor design documentation** concerns the drawings and the instructions for manufacturing and assembly causing errors in element manufacturing which were not realized until assembly (Paper II). This resulted in rework and delays during site production – a waste of time and resources. Also, the large amount of drawings and instructions was difficult to understand for production personnel which resulted in human errors (Paper II).

- **Deficient production planning** concerns the lack of scheduling production tasks which led to these tasks being executed mostly ad-hoc on the construction site (Paper III). The high variety in production output (element assembly) made any production plans difficult to execute (Björnfot 2005). Issues in internal finishing work were related to the planning of work, i.e. crew assignments were planned daily due to the low level of detail in the production schedule (Paper III).

Throughout the production process a number of wastes are readily observable, e.g. producing defective products, motion and waiting. These wastes make continuous flow difficult to achieve. Ballard et al. (2003) claimed that making work flow smoothly and reliably is the first step in performance improvement at every level in the production system. In Chapter 2.4 it was argued that the main purpose of the Lean Construction applications is production system design for increased control over construction events through the reduction of variety. In the analysis of the production process in Papers II and III (and the analysis of long-span timber structures in Paper I), applications are proposed which provide stability and better control of construction events so that waste can be reduced and work flow established. These applications specifically deal with the core issues identified above, i.e. design decisions that better support prefabrication, improved design documentation, and improved production planning.
5.2.1 Enabling work flow through standardization

In Paper II it was concluded that the failure to view prefabrication from a holistic perspective (i.e. consideration of all activities required for production) results in waste, i.e. unnecessary complementary site work where the advantages of prefabrication are lost since the project has to live with the initial prefabrication decision. Changing a prefabrication decision on the run is difficult because of the long lead times involved in manufacturing (Koskela 2003). Therefore product design decision should be thought through thoroughly. In the Element case study, first-aid solutions (Paper II, Table 2) was employed to improve the flow of work but the main issues still persisted. Simplification of the design and standardization of element sizes and work practices were in Björnfot (2005) argued to better support a construction process utilizing prefabricated construction components.

Simplification and standardization enables a stable and repetitive production process so that waste (for example rework, delays, etc.) can be reduced and flow facilitated. However, in the element case study there was clearly a lack of simplification and standardization efforts. Instead optimization of delivery was the guiding principle during design. Paper II, Figure 10, illustrates an example of how dividing and prefabricating the floor element in two parts (floor and sub-ceiling) can ease the cumbersome ceiling finishing work (Paper II, Table 3) and improve work flow during site production. Also standardizing the element sizes would reduce the risk of human errors in manufacturing and improve the learning process during assembly. Based on the analysis in Björnfot (2005), Figure 5.2 exemplifies the potential of using the standardized floor layout which was presented in Falk (2005).

![Standardized floor layout; see Falk (2005)](image)

- Analysis based on Table 4.1 and Appendix B. See also Björnfot (2005).
- Time given in days is per floor.
- Measured variety in assembly time per floor element: 10-60 min.

### Table 5.2

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<td>20</td>
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<tr>
<td>1</td>
<td>2</td>
<td>40</td>
<td>6</td>
</tr>
</tbody>
</table>

Figure 5.2 Example of how standardization influences assembly time (from Björnfot 2005).

Standardizing the floor layout so that two standard element sizes (Type 1 and 2 in Figure 5.2) could be used would reduce the number of errors passed down from design and manufacturing. As a result, waste in site production could be reduced leading to a learning
behaviour and a reduction of the large variety in assembly time (Figure 5.2). Reducing element assembly from 10-60 minutes per element to 20 minutes on average with low variance would halve the time required for wall element assembly (from four to two days) and reduce floor element assembly time to two days. Consequently, this effort would reduce the assembly cycle from nine to five days (compare to Table 4.1). A four day assembly cycle would be possible if the assembly time per element instead was reduced to 15 minutes (Figure 5.2). Of course these efforts also require simplification of connections between elements and the development of standard work practices in assembly.

5.2.2 Enabling work flow through the DSM

To facilitate standardization and simplification (i.e. constructible solutions), it was in Paper I argued that design work in construction requires close cooperation between the manufacturing and assembly processes. The Design Structure Matrix (DSM) is a method promoting constructability during conceptual design (see Paper I, Table 4). In Paper I the use of DSM was illustrated for long-span timber structure design where it provided both a holistic and a detailed view of interactions between components within the building system. In Figure 5.3, the use of the DSM in conceptual design is exemplified for the most common type of roof system for long-span timber structures. The example shows how structural design of components (represented by F) and tolerance requirements for smooth assembly (represented by G) can be modelled within the DSM (see further Paper I). Such modelling allows for visibility throughout the design process so that problems can be worked out with everyone involved before they emerge on the construction site.

<table>
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<tr>
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<th>A1</th>
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<th>A3</th>
<th>A4</th>
<th>A5</th>
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<th>A7</th>
<th>A8</th>
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<tbody>
<tr>
<td>Top chord</td>
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<td>Diagonal</td>
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<td>A1</td>
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<tr>
<td>Apex chord</td>
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<td>Tension chord</td>
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<td>A3</td>
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<tr>
<td>Apex joint</td>
<td>A4</td>
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<td>Chord joint</td>
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<tr>
<td>Apex chord to diagonal</td>
<td>A6</td>
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<td>A6</td>
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<td></td>
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<tr>
<td>Top chord to diagonal</td>
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</table>

Figure 5.3 Example of visualizing a design using the DSM (Paper I, Figures 4 and 7).

In Paper I it was concluded that the DSM is a holistic tool for systematic consideration of functional requirements. The specific Lean Construction characteristics of the DSM are its ability to visualize designs and to make design decisions understandable for all involved participants. According to Ballard and Howell (2003) the DSM is a useful technique for reducing negative iterations in design – the DSM is appropriate when a specific design
direction has been established or for the exploration of alternative design sequences. As was argued and briefly shown in Paper I, the DSM can also be used to sequence the production process. Consequently, working in accordance with the DSM can result in design and assembly documentation which is understandable by everyone involved.

5.2.3 Enabling work flow through Line-of-Balance and 4D CAD

In Paper III, two methods for improved management of on-site production was presented; production scheduling using Line-of-Balance (LoB) and production simulation using 4D CAD (See Figure 5.4 for an example). In the element case study the original production schedule (Gantt charts) was constructed with a solve-it-on-site mentality which was apparent from on-site observations of actual work. To illustrate this confusion, a LoB schedule was created (Paper III, Figure 6) which together with a 4D CAD simulation of the original production schedule (Paper III, Table 1) quickly identified and illustrated severe problems with the original production schedule.

The lack of planning for this specific project is obvious already at an early stage of the LoB schedule. Through 4D CAD simulations this obvious deficiency is observable as the start of every internal finishing activity (Appendix B) at the same time in the same location within the building, Figure 5.4 (1). The lack of any detailed planning clearly shows the solve-it-on site mentality adopted by the contractor. The lack of planning is also exemplified in Figure 5.4 (2) and (3) as congested work spaces and spaces without any work at all (for more specific details refer to Paper III, Table 1). Consequently, there are great opportunities to improve the flow of work already at an initial stage of construction projects by planning for continuous flow using LoB and then to visualize the work to be performed using 4D CAD simulations. According to the analysis performed in Paper III, these efforts allow the evaluation of schedule feasibility which potentially can improve the management of on-site production.
5.3 A value perspective on production system design

The fundamental goal of the Lean philosophy is to facilitate the delivery of customer value, a goal certainly aided by reducing waste and improving work flow. However, from the perspective of the Lean philosophy, establishing a reliable flow of work is affected by how value is specified by product and how the value stream is managed. In Table 5.1 the production system for the Element prefabrication case is conceptualized in terms of value, value stream, flow (see Chapter 5.2), pull, and perfection according to Table 2.6.

Table 5.1 Theoretical conceptualization of element prefabrication.

<table>
<thead>
<tr>
<th>Lean Principle</th>
<th>Conceptualization of Element Prefabrication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>The main customer of the element system is contractors. Besides requesting manufacturing of elements and the delivery of the elements to the construction site, the contractor also expected the manufacturer to be responsible for assembly; a responsibility the manufacturer was not ready for since the elements system used was not fully developed at the start of the project. Consequently, the manufacturer had not properly specified what is of value with their element system.</td>
</tr>
<tr>
<td>Value stream</td>
<td>The manufacturer has an efficient automated production system in place for production of the massive timber slabs. However, the manufacturer had no previous experience of working in the construction industry. As a result, the remaining work with the element system was performed by sub-contractors in a traditional manner inside the factories. Since this project, the manufacturer has contracted personnel who are responsible for the installations but still the value stream is not properly defined.</td>
</tr>
<tr>
<td>Flow</td>
<td>See Chapter 5.2</td>
</tr>
<tr>
<td>Pull</td>
<td>The element system is developed for each particular project according to the specific wishes of the contractor. However much of the activities performed remains the same. An emergent demand from contractors is to increase the degree of prefabrication of the element system and to provide with supporting services, such as assembly. In this regard the manufacturer must further develop its element system. As the lead time in element manufacturing is large (about 7 weeks for the floor elements), the efficiency of the automated manufacturing process is not fully taken advantage of. Consequently, there is still much room to work on to improve the manufacturing process and enhance customer value which would also help improve the flow of components to the construction site.</td>
</tr>
<tr>
<td>Perfection</td>
<td>This project was, by the manufacturer, viewed as a demonstrative project where they could develop their element system. During the project, work practices were continuously improved which was evident from the reduction of issues reported as production progressed. During the project the whole production system was transparent for researchers studying the project. However, not the same transparency was apparent during the design process nor was experience fully utilized from previous similar projects.</td>
</tr>
</tbody>
</table>
During the element case study, value was not fulfilled by the element system since:

- customer value was not properly defined – besides manufacturing of elements the contractor was also expecting responsibility for assembly, and
- value was not specified by product – the product design did not fully support an industrialized construction process using prefabricated components.

It seems that the lack of value management caused ripples all through the production system; since value was not properly defined the value stream was difficult to control, work flow during manufacturing and assembly was not achieved, and there was no stable foundation from where to begin improving the production system. The root causes of work flow issues seem to be rooted at the core of the production system, i.e. the specification of product value (Paper IV). Through an analysis of the element and volume production system in Paper IV it was concluded that the Volume case study represents a production system which facilitates value management from the point of view of the customer and other involved stakeholder.

In Table 5.2 the volume production system is conceptualized in terms of the theoretical framework, i.e. value, value stream, flow, pull and perfection (see also Paper IV and Paper V, Table 2). This conceptualization indicates that as a result of the well developed product, characteristics (stability and control) of the Lean philosophy can be observed throughout the volume producers’ production system. These characteristics are exemplified by:

- A stable and continuous value stream and supply chain.
- A well developed manufacturing and site assembly process.
- Customer pull through flexibility and adaptability, i.e. the manufacturing process is triggered by customer actions.
- Shared process design with suppliers and academics which facilitate continuous improvements.

Even if it seems like the volume producer’s production system embraces many characteristics of the Lean philosophy, there is still much that can be done to improve the production system through the Lean philosophy. For example, working according to the 14 principles of ‘Toyota Way’ could certainly improve the value generation process for the volume producer. However, if viewing the volume production system from the point of view of the construction process it seems the product approach facilitates the application of Lean Construction practices. To reflect this, a representative term was developed in Paper V – ‘product offer’ – which describes the product approach of the volume producer and Swedish detached housing; ‘the product offer is a well-defined and highly standardized building system which is developed from the values of the targeted customers and allows for the design of a stable and efficient long-term production system and firm control of the supply chain’. Henceforth, this definition is used to relate for the work by the case study producers.
## Table 5.2  Theoretical conceptualization of volume prefabrication.

<table>
<thead>
<tr>
<th><strong>LEAN PRINCIPLE</strong></th>
<th><strong>CONCEPTUALIZATION OF VOLUME PREFABRICATION</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Value</strong></td>
<td>The volume producer has a well established business and has for many years been producing housing based on the volume production system to fill a specific market segment (Chapter 5.1). Value is clearly fulfilled for their customers since the producer have long-term contracts with some landlords. Internal value for the producer is specified in their highly industrialized production system which is inspired by the efficiency of the Swedish detached housing industry.</td>
</tr>
<tr>
<td><strong>Value stream</strong></td>
<td>The volume producer controls the whole value stream which includes long-term relations with subcontractors who are brought in-house to perform their work, with assembly teams all over Sweden for efficient on-site assembly, and with important suppliers for a stable supply chain. Consequently, practices are standardized and the value stream is well established.</td>
</tr>
<tr>
<td><strong>Flow</strong></td>
<td>The manufacturing process for the volumes has been developed for many years using experiences from the detached housing industry and projects led together with academia. These efforts have reduced waste and the production system is well supported by automation and computer based information systems for improved control to further facilitate flow.</td>
</tr>
<tr>
<td><strong>Pull</strong></td>
<td>Manufacturing of the volumes is not begun until a certain amount of design is finished – in a fashion the customer pulls production. The volume system represents a well known, high quality product with predefined characteristics. Client involvement is mainly limited to interior and façade design which allows for short lead times. For the producer’s main customers the volume system offers appropriate flexibility. The producer is also continuously working on adapting the volume system to reach new market segments.</td>
</tr>
<tr>
<td><strong>Perfection</strong></td>
<td>The stable value stream enables the volume producer to utilize transparency and to generate improvement programs which aim at improving customer value and work practices. These programs are often worked on together with key suppliers as well as with academics.</td>
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### 5.4 Value generation through ‘product offers’

From the perspective of the Lean philosophy the ‘product offer’ represents a value view on Swedish industrialized construction since customer requirements are what defines the building system which in turn allows for the design of a production system that conform to the Lean philosophy (Table 5.3). The definition of the ‘product offer’ complies with Garnett et al. (1998) conclusion that delivering customer value means organising around a product that provides continuity and stability. As explained above, the ‘product offer’ seems to make it possible to control the variety of the traditional project oriented construction process (Chapter 2.3) through continuity and stability which in Chapter 2.4.3 was argued as the primary objective of Lean Construction applications. Consequently, the ‘product offer’ definition can be viewed as an application of the Lean philosophy for
multi-storey housing construction which facilitates value generation throughout the production system (Table 5.3 – see further Paper V for an explanation of table contents).

Table 5.3  The characteristics of the ‘product offer’ (presented as Table 2 in Paper V).

<table>
<thead>
<tr>
<th>Lean principle</th>
<th>The ‘product offer’ implies…</th>
</tr>
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<tbody>
<tr>
<td>Value</td>
<td>…detailed product specifications developed from customer requirements captured on the market where the product is intended.</td>
</tr>
<tr>
<td>Value stream</td>
<td>…definition of the specific resources and activities required for supply chain management and product realization.</td>
</tr>
<tr>
<td>Flow</td>
<td>…control of a stable value stream so that value adding activities can be better managed and so that waste can be eliminated or reduced.</td>
</tr>
<tr>
<td>Pull</td>
<td>…flexibility and adaptability to current and future customer demands and the ability to find ways of reducing lead times.</td>
</tr>
<tr>
<td>Perfection</td>
<td>…stable and transparent processes and operations allowing for continuous improvements by experience feedback.</td>
</tr>
</tbody>
</table>

Based on the characteristics of the ‘product offer’ (Table 5.3), it was in Paper V argued that the application of the ‘product offer’ approaches Lean Construction on a strategic level (i.e. from a business perspective) since value management is applied to production system design. This is an initial step in transforming an organization to Lean which allows focus to be directed to managing the transformed organization so it remains Lean. This view coincides with the first stage of Leanness as described in Green and May (2005). By integrating the variety of the construction process into the product (e.g. client demands, component supply, structural design, etc.), the ‘product offer’ provides a stable foundation for client negotiations, design development, production system design, supply chain management, and continuous improvements of both the product and associated processes. This enables producers to satisfy customer requirements while pursuing profitability through stable production systems and supply chains.

In Paper V the four main aspect of ‘product offer’ development was identified; 1) product specification, 2) internal relations 3) external relations, and 4) supply chain management. The volume/element case study can be considered an example of a ‘product offer’ development initiative. The results from this case study indicate that the development of the ‘product offer’ both utilizes and has the potential of enabling Lean practices:

- The highly standardized product facilitates development of standard work in manufacturing and assembly.
- Internal relations between the involved producers are managed through target costing and relational contracting.
- External relations with customers are managed through flexibility in product design which is limited to protect the stability of the production system.
• The supply chain is managed through long-term supplier relations which enables transparency and possibilities for continuous improvements.

What the ‘product offer’ fundamentally boils down to is the matching of standardization with flexibility. In Höök (2005) this ‘struggle’ was conceptualized as an increased product complexity (leading to reduced production efficiency) as customer influence is increased (customization). In this regard, the ‘product offer’ can be considered to combine the Lean and Agile production paradigms (Figure 5.5) which focus on process efficiency and responsiveness respectively (Naim and Barlow 2003). The combination of these paradigms (Figure 5.5) is what defines the value proposition of the ‘product offer’, i.e. the flexibility required to satisfy customer value and the standardization needed for efficient production. Support for this view can be deducted from Browning (2003) who argues that it is not only about providing customer value – customer value must be balanced with stakeholder value in a firm’s value proposition. Naim and Barlow (2003) argue that the Lean/Agile approach is achievable through elimination of waste in supply chains and the maximization of customer service, especially flexibility, at an acceptable cost. These are activities the ‘product offer’ strives to balance out in its value proposition (Figure 5.5).

Figure 5.5  Value delivery through product offers.

In value delivery the ‘product offer’ is more related to manufacturing than contemporary construction. The production system is based on what can be manufactured in the most cost-efficient manner while the customer receives a product that fulfils value, as long as the technical platform fulfils customer requirements. Such a compromise in value generation and delivery allows producers utilizing ‘product offers’ to engage in projects where profitability can be assured. In this fashion, the ‘product offer’ is able to better control the variety of construction (and reduce waste) through prefabrication. The ‘product offer’ can also be considered to represents a solution to one of the hidden wastes of construction – construction companies trying to become best at everything by pursuing every possible project (Josephson and Saukkoriipi 2005) instead of pursuing projects where the product offered provides with additional value over their competitors.
6 Discussion and conclusions

Chapter 6 discusses and concludes the results presented in this thesis. Answers to the two aims of this thesis are provided and the contributions are specified before future research opportunities are recommended. The research validity and the generalization of the findings are also evaluated.

6.1 Lean Construction: its development and research opportunities

In many world markets, no single company seems able to produce products (deliver value) for every type of customer, since customer value is continuously changing depending on a range of parameters, such as word of mouth, usefulness, price, etc. Therefore, there are brands such as Volvo and BMW in the automotive industry, and IBM and Dell in the computer industry. Business in construction is conducted through project management (i.e. cooperation between many different stakeholders who often have no previous relations), which is considered the primary way of value delivery (Chapter 2.4.1). In this regard, Ballard and Howell (2004) claim that designing and making products the first time is what construction projects are all about, placing construction firmly in the same class with other project-based production systems, such as shipbuilding and movie production.

Lean Construction research is frequently categorized by its peculiarities, i.e. one-of-a-kind production, site production, temporary organizations, and governmental control (Höök 2006). These peculiarities are often used to explain the failures of transforming construction to Lean (Koskela 2000). Why is construction differentiated from manufacturing? The business goal is obviously no different (i.e. deliver value to the customer), and manufacturing is now extensively used in construction through prefabrication (considered representative for Swedish housing construction). In retrospect to the early days of Lean Production, the Toyota Production System (TPS) was fundamentally a new business model that represented a framework of concepts and methods to enhance corporate vitality (Fane et al. 2003). Consequently, Lean Production is represented by new production methods and more efficient organizations. Fane et al. (2003) argue that the most significant barrier for non-Japanese firms to fully adopt the TPS model is the necessity of a larger commitment to the firm, its products and customers.

For construction, Ballard and Howell (2004) view the Lean philosophy as a new paradigm whose goal is to deliver the product while maximizing value and minimizing waste. This extensive perspective should involve production innovations and organizational change. However, the development of Lean Construction theory has mainly focused on methods to facilitate work-flow by the fine-turning of traditional construction practices (Chapter 2.4.3). It seems as though the organizational change of a Lean transformation has been partially forgotten in Lean Construction research; more specifically, the question of how construction should be structured to best generate value for the customer is rarely dealt with. Value management in construction has not received enough attention so far (Winch 2006) which is surprising since the Lean philosophy in itself is about finding root causes to
problems (Chapter 2.5). In Chapter 5.3, the lack of value management was identified as a cause for work-flow issues in multi-storey timber housing construction.

From a value perspective, the common and pre-dominant project-based production mode of construction should only be viewed as a means to deliver customer value. Winch (2006) hints at this by stating that repetitive operations are not appropriately arranged in project mode. The project should instead be considered as one possibility, among others, of delivering value to the customer. From the analysis of element prefabrication (Chapters 5.2 and 5.3) it seems like the influence of the traditional project-oriented construction process is restraining production management, i.e. the observed work-flow issues ultimately originate from a failure of value management in an industrialized construction context. Results from the volume (Chapter 4.2) and volume/element (Chapter 4.3) case studies indicate the possibility to join together and deliver value in new ways for multi-storey timber housing construction by organizing around a construction product.

The development and adaptation of the understanding of Lean Construction in relation to industrialized construction can be summarized as:

- The development of applications for Lean Construction has mainly focused on improving the flow of work, i.e. the fine-turning of construction practices in design, supply, and assembly (Chapter 2.4.3) has led to improvements in the management of production for traditional site-built construction projects.
- There is more to understanding Lean Construction than production management (see e.g. Table 2.6). To support this statement, Green and May (2005) argue that in the development of Lean Construction it is implicitly assumed that the organization is already Lean. Consequently, a value approach to the Lean philosophy is needed to fully realize its benefits.
- There are great opportunities to develop innovative approaches to value delivery through a more comprehensive understanding of the underlying Lean philosophy. Current Lean Construction development trends, such as experiences with relational contracting (or integrated coalitions) (Matthews and Howell 2005, Koskela and Ballard 2006), are a strong indication that it is possible. In this regard, the ‘product offer’ represents an example of applied Lean Construction research.

6.2 The ‘product offer’ – what it is and what it isn’t

Although being a limited study in size and scope, the results of the case studies presented in this thesis indicate that the Swedish multi-storey timber housing industry is slowly changing from a traditional project-based generation of customer value to offering specific products that can be individually adapted within pre-specified limitations. This enables companies with well-developed ‘product offers’ (Chapter 5.4) to better control their value stream and manage customer value, while continuously improving on their work as waste
is eliminated. Experiences from the study of long-span timber structures (Björnfot 2004) indicated that the observed high productivity and quality during production is based on a bottom-up view where a focus on the product design enables stability and better control throughout the production system and associated supply chain. Consequently, the long-span timber structure case can be considered to represent a value perspective on production system design similar to the volume and volume/element case studies.

Of primary importance in a ‘product offer’ development initiative is to first specify customer value and then to deliver it to the customer in a cost-efficient manner. Managing customer value through the ‘product offer’ forces the customer to lock-in their options to a specific technical platform (building system) offered by the producer. Locking-in customer options allows the producer to be in control of a stable value generation process where customers are allowed flexibility through selected add-ons and options. Consequently, the ‘product offer’ allows value to be specified by specific products for specific customers. Control over the value generation process enables stability and better control of product development, manufacturing, supply, and distribution (Chapter 5.4), i.e. the ‘product offer’ can be considered to represent the heart and lifeblood in an organization striving to improve the whole production system (Figure 6.1).

![Diagram of 'product offer' as a driver of production system design](image)

Figure 6.1  The ‘product offer’ as a driver of production system design (see also Figure 2.2).

A negative aspect with the ‘product offer’ from the clients’ point of view is their limited ability to influence the design process. Additionally, limited markets with limited competition may result in reduced diversity, since the ‘product offer’ caters to specific customers and is clearly not suitable for everyone. There is also a fear from society (clients, architects, and people in general) that increasing the degree of prefabrication would incur a number of similar ‘boxes’ spread evenly throughout the landscape (Boverket 2005). However, from a value perspective, society would never accept this since value would not be fulfilled. Therefore, the architect has an important role (albeit a different one) in an industrialised construction process; in the volume/element development initiative (Chapter 4.3) the architects’ role is to provide varying design in direct support of a product, e.g. façade, floor layouts, etc. A majority of Swedish contractors, architects and consultants believe that the architects’ role must become more product-oriented with the introduction of industrialized construction (Industrifakta 2006).
CHAPTER 6 DISCUSSION AND CONCLUSIONS

What the product offer represents and what it does not can be summarized as:

- The ‘product offer’ is a representative term that describes the technical platform adopted by some Swedish detached and multi-storey housing producers who offer added customer values based on factors that extend beyond functional performance, such as long-term quality assurance and financial aid.
- The ‘product offer’ represents a Lean Construction application for enabling stability and control throughout the production system and supply chain for multi-storey housing construction (Chapter 5.4), i.e. the ‘product offer’ increases the predictability of process outputs by controlling the variety of its inputs.
- It should be noted that using a ‘product offer’ does not automatically enable the design of a production system to conform to the Lean philosophy. Rather, the ‘product offer’ represents the first step in a Lean transformation because it provides knowledge of what is required to take the next step by focusing on the delivery of value, i.e. the fundamental aim of the Lean philosophy.

6.3 Conclusions and contributions

The first aim of this research (Chapter 1.3) was to explore how the theory of Lean Construction can be used to gain a deeper understanding of the Swedish multi-storey timber housing production process and how this process can be improved through Lean Construction theory. The following points conclude the findings of this research in relation to this aim:

- Understanding the production process as a flow of work (Chapter 2.4.3) enables waste to be identified and hence eliminated or better controlled through the use of common Lean Construction applications for product design and production planning (see Chapter 5.2).
- Applying a holistic perspective of the Lean philosophy (Table 2.6) to the production process can help identify root causes to work-flow obstructions and spur the development of more effective organizations for value delivery (Chapters 5.3 and 5.4).

The second aim (Chapter 1.3) of this research was to explore how knowledge of contemporary Swedish multi-storey timber housing can help extend the theory of Lean Construction to provide a deeper understanding of industrialized construction. The following points conclude the findings of this research in relation to this aim:

- From the definition of the ‘product offer’, industrialised construction can be viewed as applied Lean Construction research. Consequently, industrialized construction extends the theoretical Lean Construction framework to include
research fields that focus on value management as means of delivering value to customers, such as relational contracting and ‘product offers’.

- A value perspective on volume prefabrication indicates that by specifying value through a specific product, the transformation to Lean Construction for multi-storey housing construction is facilitated (Chapter 5.4). This view enables new fields of research within Lean Construction that facilitate value management, such as marketing (e.g. Davison et al. 2006) and specialization (see Chapter 6.5).

### 6.3.1 Scientific contributions

Prefabrication has a future and the development of ‘product offers’ suggests that prefabrication is firmly related to Lean Construction, if viewed from a value perspective. The specialization trend of the Swedish housing industry, a trend not only limited to timber, seems not to be internationally common. Therefore, the main scientific contribution of this research is the description of this industry, and in particular how new forms of value delivery utilizing prefabrication can be regarded as change agents in the adoption of Lean Construction for multi-storey housing construction. The Lean philosophy is about value delivery approached by the ‘product offer’ through cooperation within long-term and stable production systems and supply chains. Additionally, viewing prefabrication from a value perspective provides new input in the discussion of its role within construction management and its inability to provide architectural freedom.

A fear from a theoretical perspective is that the term Lean Construction can become meaningless, i.e. many construction management research fields are already associated to Lean Construction theory since their aims and approaches seem very similar. Consequently, Lean Construction might become nothing more than a ‘buzzword’ because the fundamental message of the Lean philosophy becomes entangled in specific applications or practices. There certainly are circumstances where improved production control (for example through the Last Planner System) can have a profound effect on production management, e.g. complex industrial projects constructed in a traditional manner. However, the theoretical advancement of Lean Construction could benefit from a revisit to the roots of the Lean philosophy; Swedish industrialized multi-storey housing construction is an example of this approach to Lean Construction research.

### 6.3.2 Practical contributions

Because large contractors are focusing more on managing projects, they will ask producers (which they already do) to take on a greater responsibility in the construction process as well as, besides manufacturing products, ask for supporting services such as assembly. This is the first step in developing a ‘product offer’ by finding out what the customer is willing to pay for and become best at what you do. Increase profitability by finding a unique role
within the construction process, specialize in your main products and services, cooperate with your most important suppliers, and from there continue to improve by constantly offering the customer more value for his money while improving your production system. This implies that one company cannot become best at everything, but rather pursue projects where significant value can be offered over your competitors! To aid in this development process, apply specific Lean Construction applications that aid your work in designing a stable and long-term production system and supply chain, e.g. identify and deal with waste through value stream mapping (Rother and Shook 2001) or the principles of Toyota Way (Likert 2004).

6.4 On research generalization and reliability

Do the results presented in this thesis only apply to multi-storey timber housing construction? The description of industry specific practices is certainly associated to this type of construction. However, considering that work-flow improvements are the main thrust of Lean Construction – to enable work-flow, the variety must be reduced by increasing the predictability of construction output (Chapter 2.4.3) – these issues are certainly not unique to multi-storey timber housing construction. Therefore, the suggested applications for work-flow improvements (Chapter 5.2) and the understanding of their root causes (Chapter 5.3) can be considered general for construction as well. Of course, what are the root causes and what applications are best suited to improve work-flow depends on the construction setting, e.g. housing, industrial, infrastructure, etc.

The results from the volume case study concern the practices of one company, while the results from the volume/element case study concern one delivery team. The volume case study describes practices specific to the volume producer. These results are used to argue for a value perspective on multi-storey timber housing construction (Chapter 5.3). This value perspective is not unique to multi-storey timber housing construction since the same specialization trend is observable in detached housing, i.e. a different industry with different customers, and for other materials, e.g. concrete in the case of NCC KOMPLETT (NCC 2006). However, these results are still based on Swedish conditions even though they show that a value approach to Lean Construction research is possible and in some cases even preferred. The ‘ideas’ of the delivery team in the volume/element case study are used to deepen the knowledge of ‘product offer’ development and should therefore be viewed as an example of industrialized construction research supported by Lean Construction theory.

How can research reliability be assured for construction practices in a changing market? This discussion is mainly relevant for the element case because the results from the other two case studies describe activities considered common for the Swedish development of industrialized construction (see e.g. Boverket 2005), i.e. either realized in the volume case or strived for in the volume/element case. Since one aim of this thesis was to explore the applicability of Lean Construction for contemporary Swedish multi-storey timber housing
construction, the element case study fits in well as a case study of contemporary practices (Table 3.1). Because the case study results cover many different perspectives of the production system, they cannot be considered sufficiently extensive to provide any conclusive evidence in the development of specific Lean Construction applications or practices. However, as a foundation for the theoretical evaluation of Lean Construction the results provide an understanding of the possibilities and deficiencies of Lean Construction theory. Due to the lack of empirical data, this theoretical evaluation is the main contribution of the research presented in this thesis.

6.5 Future research

The research and drawn conclusions presented in this thesis open up Lean Construction theory and applications to research fields specifically related to a value perspective, i.e. (from Table 2.6) define the customer, define what is of value to the customer, define what is of value to the delivery team, and define how value is specified by products. Below are future research fields that should aid research on value management, provide a wider perspective on industrialized construction, and strengthen Lean Construction theory and development:

- **Product branding.** Branding differentiates a product from its competition by specifying the values to be delivered to the market and the values of the brand owner themselves (Davison et al. 2006). This initial study suggests that a brand is related to the building itself, involved participants, type of components used, and the services offered. Research on branding should strengthen the practical application of ‘product offers’, and also strengthen research of industrialized construction in relation to Lean Construction. In this regard, the Swedish industry with its specialization trend should have much to offer the international research community.

- **Specialization.** On what conditions should a construction component producer choose to specialize in specific products or product families? How are the core products and core services of a producer identified? Who should act as the pull mechanism in transforming a specific construction segment to industrialized construction? ‘Who will rationalize the value stream and when?’ (Womack et al. 2003). What will become of the roles of the current construction process participants? What will their future roles be?

- **Relational contracting.** How can construction participants cooperate to better deliver value to the customer? Who should be involved in such cooperation? First and second tier suppliers? Manufacturers? Design firms? Architectural firms? Trucking companies? Local assembly teams? How should this cooperation be executed to avoid competing with self-interests?
7 References


CHAPTER 7

REFERENCES


PAPER I

A DSM approach displaying structural and assembly requirements in construction

By: Anders Björnfot and Lars Stehn

(The paper has been edited to fit this thesis format, but the contents remain the same)

A fundamental demand of construction design is human safety from structural failure. As a consequence, buildings generally tend to be structurally optimised with cost as the main target parameter. However, a cost sub-optimised structural design often leads to poor constructability decisions with subsequent waste. This paper presents initial research in the development of a Design Structural Matrix (DSM) method able to identify constructability obstacles between structural design and assembly and thus eliminate waste. Empirical data based on a case study of long-span timber structures is used in the development and analysis of the method.

The DSM was found to be a holistic tool for systematic consideration of structural design and constructability requirements by providing a standardised system view, a detailed element view, and physical and functional interactions among elements and modules. The DSM was also shown to aid in detailed design and production management through the use of simple matrix tools.

Keywords: Assembly; Constructability; Design Structure Matrix; Modularity; Standardisation

1. Introduction

In recent years, industrialisation has been a widely debated issue in construction research (e.g. Ballard et al. 2001, London and Kenley 2001). Implementing industrialisation in construction is a way to reduce non-value adding craft-based activities, i.e. waste elimination (Koskela 2003). For this purpose, construction has directed attention towards the manufacturing industry in an attempt to learn, or in some cases even copy, successful concepts (Gann 1996). However, the implementation of manufacturing concepts in construction has often failed due to an increased complexity in the management of construction projects compared to the production of manufactured goods (Koskela 2003).

Compared to most manufactured goods, buildings are large, immobile one-of-a-kind products mainly site-built where the place of assembly is different from the place of component manufacturing. Each component (e.g. doors, windows, walls, etc.) is designed, manufactured, and processed by many construction participants (e.g., designers, manufacturers, contractors, etc.) who have their own set of goals and requirements (Björnfot and Stehn 2005). Although construction has many peculiarities not present in
manufacturing, its uniqueness is not extreme from the point of view of production and operations management (Koskela 2003).

A fundamental demand on construction design is human safety from structural failure (collapse), as regulated by the government (building codes) on all constructed buildings. As a consequence, buildings generally tend to be structurally optimised with cost as the main target parameter. On the other hand, one of the main characteristics of a lean production process is manufacturability. Similarly, a main characteristic of a lean construction process should be constructability (Fisher and Tatum 1997). The results of poor constructability decisions in construction design are commonly evident from tolerance issues (Tsao et al. 2004) and poor working conditions (Björnfot and Stehn 2005). A cost sub-optimised structural design may therefore lead to poor constructability decisions with subsequent waste.

This paper presents initial research on the development of a method integrating structural engineering and constructability requirements in timber housing construction. The method under development is based on the engineering design method/tool Design Structural Matrix (DSM) and is not intended as a design toolkit. Rather, its purpose is to identify constructability obstacles between structural design and on-site assembly and thus eliminate waste. Empirical data based on a case study of long-span timber structures performed at a leading Swedish design company is used in the development and analysis of the method. The case study comprised interviews and a survey of 60 previously built long-span timber structures.

2. Industrialised construction: design and assembly requirements

One of the main characteristics of lean thinking, and the industrialised construction process, is the elimination of waste, i.e. overproduction, correction, material movement, processing, inventory, waiting, and motion (Haque and James-Moore 2004). To reduce or completely remove waste in a construction project, each construction participant involved in the process must realise how their work is influenced by, and affects, the work performed by other participants involved. This allows each participant to evaluate constructability requirements considered a prerequisite for successful project initialisation and outcome (Tatikonda and Rosenthal 2000). The constructability requirements of each participant in physical product design and construction site assembly are evaluated from Björnfot and Stehn (2005) (see table 1). The table should be read row-wise where each diagonal entry explains the main assignment of each participant and each cell reveals the information required from other construction process participants. In this paper, the participant requirements in table 1 are used to evaluate and discuss the usefulness of the DSM method under development.

2.1 Construction product modularity

Mass production, utilising standardised parts and prefabricated components, has been a prevailing concept in the automotive industry for almost a century (Crowley 1998). Standardisation and prefabrication are commonly linked together with modularity,
Table 1. Constructability requirements in structural design and construction site assembly 
(evaluated from Björnfot and Stehn, 2005).

<table>
<thead>
<tr>
<th>Designer</th>
<th>Manufacturer</th>
<th>Contractor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Provides the products with physical properties subject to all customer demands.</td>
<td>Requires knowledge of designs and details which reduce manufacturability of products.</td>
<td>Requires knowledge of how the products are joined together and the order of assembly.</td>
</tr>
<tr>
<td>Requires dimensional coordinates and detailed knowledge of tolerances requirement.</td>
<td>Provides the product with physical dimensions and delivers the manufactured product to its place of use.</td>
<td>Requires knowledge of assembly operations and logistics information for site delivery.</td>
</tr>
<tr>
<td>Requires information of the product designs of all involved products for site task planning.</td>
<td>Requires delivery and manufacturing information for planning of assembly operations.</td>
<td>Plans the assembly of the products into their final place in the structure and executes the plan.</td>
</tr>
</tbody>
</table>

defined as the division of a whole into sub-entities, which to a significant extent are compatible and independent (Sarja and Hannus 1995). Modularity can be argued to be a key concept in the manufacturing industry, resulting in flexibility and efficiency (Gann 1996) by effectively incorporating concepts like manufacturability (Sharma and Gao 2001) and theories of lean and agile production (Naim and Barlow 2003).

Modularity in construction has frequently been viewed as the use of simple building blocks (Rampersad 1996) or volumetric pre-assemblies (figure 1) (Murtaza et al. 1993). A module contains specifications of a building block and its interfaces, as well as considerable functionality compared to the end product (Miller and Elgård 1998). Modules can be defined by grouping elements such as beams, nails, etc. together and then identifying interactions among the elements and between the modules; the interactions required are both geometric (physical) and functional (Marshall and Leaney 2002). Based on the module definition all products are somewhat modular (Schilling 2000). Therefore, the modular division of the system (product) is not the essence of modular products; rather it is the standardised way of thinking what such a division provides.

For buildings, standardisation is often used to systemise physical interfaces between construction products, and to reduce the amount of information processing required for design. This standardised way of thinking is perhaps most evident in the volumetric pre-
assemblies used by some Swedish construction companies (figure 1). The volumes are composed of numerous partly standardised modules, e.g. floor module, wall module, roof module, etc., fitted together into volumes using standardised interfaces. Therefore, taking advantage of the inherit modularity of construction products can provide the standardisation required to achieve constructability and future waste elimination.

3. Engineering design using the Design Structural Matrix (DSM)

Methods/tools commonly used in engineering design are often based on fuzzy logic. One of the most common fuzzy logic methods is Quality Function Deployment (QFD). QFD is frequently used in both manufacturing and construction, where the main goal is increased product quality, while providing customers with desirable products (Stehn and Bergström 2002). Common to QFD and other fuzzy design methods – Analytical Hierarchical Process (AHP) (Weck et al. 1997) and value engineering (Al-Hammad and Hassanain 1996) – is the required qualitative (fuzzy) input from users/professionals that is then converted to quantitative measures based on a rating system. However, the main source of design and assembly knowledge in construction is feedback (professional input) from constructed structures (Fischer and Tatum 1997). An ideal representation of a constructional structure requires a holistic systems view, a detailed element view, and physical and functional interactions among elements and modules. QFD and other studied design methods based on qualitative inputs are unable to effectively manage this complexity. Therefore, any representation of product modularity is preferably performed using matrix methods or tools where relationships between components can be visually represented and evaluated (Gershenson et al. 2004). The Design Structural Matrix (DSM) is a matrix method capable of managing functional requirements and a wide array of element interactions.

The DSM displays the relationship between the components of a system and offers design evaluation using well-known matrix tools (Browning 2001). DSM also seems to fulfil the requirements of product modularity providing a holistic and detailed view of interactions between modules and system elements. DSM has indeed been used to model and analyse product modularity (e.g., Martin and Ishii 2002). A DSM is a square matrix with identical row and column labels. In the component-based DSM, figure 2, their

<table>
<thead>
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<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
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<tr>
<td>A</td>
<td>A</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td></td>
<td>B</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>C</td>
<td></td>
<td></td>
<td>C</td>
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<tr>
<td>D</td>
<td></td>
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<td>E</td>
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Figure 2. Example of a DSM and its interpretation.
characteristic letters in the diagonal represent the elements. An off-diagonal mark signifies a dependency of one element on another. Reading across a row indicates outputs, i.e. which elements the element influences; scanning down a column reveals input sources, i.e. which elements the element depends on; and an empty square in the matrix represents no relationship.

The component-based DSM in this paper is used to model a timber structural product. Row and column summation is used to analyse and evaluate the integration of structural engineering and constructability considerations in long-span timber construction. Many requirements (a summation of off diagonal DSM marks, e.g. figure 2) on a part of a system indicate the need for increased attention during design. For example, the focus during design of the product represented by the DSM in figure 2 should be element C, where four requirements from three other elements are considered. Martin and Ishii (2002) also used summation of requirements and constraints among modules to evaluate the design of products.

4. Research method

In this paper, the structural system for a common type of non-insulated long-span timber structure, figure 3, is used as an exploratory example of DSM modelling. Long-span timber structures were chosen as the research framework because of the second author’s 10 years of experience as a practicing designer of timber structures, as well as the structural system for long-span timber structures being relatively easy to comprehend compared to, e.g. multi-storey structures where other technical systems (such as heating, ventilation and air-conditioning) often must be considered. In the initial DSM development the following hypothesis is used: if the DSM method is able to model one functional requirement in detail then other functional requirements can be modelled in the same way.

4.1 The case study

A single case study at a Swedish design company was used to study its design and assembly of long-span timber structures. The case company is one of five specialised design companies and can be characterised as a construction management firm offering structural design and management of on-site assembly for long-span timber (and to some extent steel) structures. The company has three employees and has been competing on the Scandinavian construction market since 1986. The managing director (MD) has 30 years of experience as a designer. The company’s extensive knowledge of design and production together with the MD’s broad knowledge of the Swedish construction industry was the main reason for choosing them as the case company.

This single case study is based on two phases, interviews and a survey. The aim of the interviews was to collect general and specific information about the structural system and the design and assembly processes. The MD and employees were continuously interviewed over a six-month period. Each interview yielded a growing understanding, resulting in further interviews and the survey. The survey consisted of 60 long-span
timmer structures constructed by the case company from 1994 to 2001, equal to around 10% of all long-span timber structures constructed in Sweden during this time. The structural system was studied by reviewing design choices, calculations, and drawings. The assembly process was studied by reviewing time schedules, quality control plans, drawings, other pertinent documents and an extensive supply of photographs.

The choice of one company for the case study is not seen as a hindrance to validity and generality due to the MD’s extensive experience and the small Swedish market for such structures. Actually, from a systems perspective, the design solutions among different companies are almost identical. The differences in solutions are mainly concerned with the detailing of interfaces. Comparing the interview and survey results with the MD and second author’s knowledge and understanding of long-span timber structure design and assembly permitted triangulation of the case study results presented here.

5. Case study results

Interviews with the MD indicated the structural system to be the most important technical sub-system for long-span timber structures, figure 3, since a thorough design of the structural system is the foundation for efficient design of other technical sub-systems (e.g. heating, ventilation and sanitation). The structural system, whose purpose is to carry the vertical and horizontal external loads from the structure to the foundation, is made of six different sub-systems each composed of timber beams and steel joints connecting them together (except for the stabilising systems that are commonly composed of tension rods in steel). Figure 3 shows the joints between the sub-systems, as indicated by circles.

The selection of structural sub-systems is mainly based on economic considerations, table 2. The most important sub-system is by far the roof system, accounting for up to 70% of the total cost, including material and assembly (personnel and machinery) of the structural system. The design of the roof system is also important from a production viewpoint, since its assembly requires many sub-assemblies and the use of expensive machinery (mobile cranes) (Björnfot and Stehn 2004).
Table 2. Overview of total costs based on case company experience.

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Total Cost (€/m²)</th>
<th>Ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof</td>
<td>26</td>
<td>70</td>
</tr>
<tr>
<td>Roof-purlin</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Column</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stab. in roof</td>
<td>9</td>
<td>30</td>
</tr>
<tr>
<td>Stab. in wall</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wall-purlin</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>35</td>
<td>100</td>
</tr>
</tbody>
</table>

One of the most common roof systems used by the case company is the pre-stressed tied rafter, represented by four structural elements and four joints, figure 4. The structural elements of the roof system are delivered to the construction site where they are assembled to a complete roof structure. A force is then applied to the Apex chord to reduce the bending stresses in the Top chord. Pre-stressing of the system provides the system with its distinctive name. The pre-stressed tied rafter contains a large number of elements and joints making it an illustrative example of sub-system systematisation and DSM modelling.

5.1 Case study results discussion

The goal of the case company in product design and construction site assembly is low cost utilisation of the material and structural optimisation together with an accurate fit for smooth assembly. Structural optimisation and accurate fit require holistic views at the structural level (optimising and fitting the structural system as a whole) and internal interactions at the sub-system level (optimising and fitting the elements and joints within sub-systems). Since the purpose of the structural system is to fulfil its load carrying function, the interaction between all elements and joints must be considered in structural design. The case company clearly uses a holistic structural view where the design and assembly phases are jointly considered.

The inherent modularity of the structural system, viewed as the clear division of the structural system in sub-systems, has been a guiding star in achieving constructability. This is apparent from the use of standardised interfaces between sub-systems independent
of the type of sub-systems used. For assembly of the structural system, the constructability from this standardisation has resulted in an efficient and quick assembly process (Björnfot and Stehn 2004). In this paper, the DSM is used to capture the case company design process, a process which has been successful in delivering constructible structures at low cost. For modelling purposes, structural design is limited to the fundamental functional requirement of human safety, i.e. the design of vertical and horizontal load-carrying capacities represented by the interaction of forces among elements and joints. Constructability constraints in on-site assembly are limited to the geometric fit of elements and joints for smooth on-site assembly.

6. DSM structural modelling

Complete modelling of the structural system requires the holistic structural system view detailing interactions among sub-systems, as well as detailing interactions among elements and joints on the sub-system level. This calls for a DSM hierarchy composed of two types of DSM - structural DSM and sub-system DSM, figure 5. In Structural DSM, each DSM layer displays detailed interactions among sub-systems (A, B, etc.) for one functional requirement (e.g. FR1), creating a form of 3-D DSM hierarchy where each diagonal entry in the structural DSM describes one specific sub-system in detail, the sub-system DSM. The sub-system DSM has the same hierarchy, but instead displays detailed interactions among elements and joints (D1, D2, etc.) for the considered functional requirements. Each diagonal entry in the sub-system DSM contains detailed information of an element or joint connected to the studied sub-system. To accommodate more complex structures, or products, containing more sub-systems or elements, the DSM can be extended by another row and column for each sub-system or element/joint. More functional requirements can be considered by simply adding another DSM layer to the DSM hierarchy, FR2, FR3, etc.

Figure 5. The Hierarchical DSM disposition of the structural system.
6.1 Structural DSM

The row and column labels and the DSM entries in the DSM models (Figures 6 and 7) are all obtained from the case study (Figures 3 and 4). The sub-system and element/joint interactions are interpreted as described in Figure 2. Using structural knowledge gained from the survey, the DSMs are created row-wise, cell by cell, by asking the questions, ‘Does any load transfer between the sub-systems occur?’ and ‘Do any geometrical constraints exist between the studied sub-systems?’ Load transfer between sub-systems or elements/joints is indicated by an F, and a geometric constraint for on-site assembly is indicated by a G. Empty cells in the matrix consequently imply no functional relationship. The structural DSM in Figure 6 is a detailed representation of the structural system presented in Figure 3, illustrating interactions between modules. For ease of interpretation, the functional layers F and G are mapped in the same DSM (compared with FR1 and FR2 in Figure 5).

Understanding DSM modelling requires detailed knowledge of the interaction between externally applied forces and sub-systems, elements and joints in the structural system (Figure 3). As an example from Figure 6, the roof-purlin system (B) transfers forces (F) to the roof system (A) when vertical loads or horizontal loads are applied to the structure, i.e. forces from the roof-purlin to roof interface (BA) in both cases. The DSM for the geometric constraints (G) is symmetric around the diagonal. Symmetry for the

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Figure 6. The structural DSM for long-span timber structures, illustrating both force transfer (F) and geometric constraints (G) among the sub-systems.
geometric constraints implies that, for example, changing the cross section of the top chord of the pre-stressed tied rafter (roof system) conveys a change in the cross section of the columns, and vice-versa. Lin and Chen (2002) also found a symmetric DSM efficient in modelling constraints between modules.

6.2 Sub-system DSM

The sub-system DSM illustrates interactions among the elements and joints within a module. The pre-stressed tied rafter is used as an example of detailed sub-system modelling. The row and column headings of the pre-stressed tied rafter DSM in figure 7 can be realised by studying figure 4. This DSM is interpreted the same way as the global DSM and is actually the diagonal entry A in figure 6 (hence, the column/row entries are labelled A1 to A8).

6.3 Structural and sub-system evaluation

The use of summation for DSM evaluation is shown for the structural DSM in figure 6 and the sub-system DSM in figure 7. The functional requirements and the geometric constraints of each sub-system, interface, element, and joint are added up row- and column-wise forming “design sums” which highlight the need for increased attention during the design of sub-systems/interfaces and elements/joints. Table 3 shows an example of how summation can be performed for the structural sub-systems and the elements of the pre-stressed tied rafter.

The “design sums” represent integrated design and assembly considerations. Because a high “design sum” indicates a need for increased attention during design, the roof system (A) should be the primary sub-system during the design and optimisation of a long-span timber structure, since the roof system transfers forces to five other sub-systems while considering forces from six sub-systems during its design. The roof-system
also needs increased attention from an assembly viewpoint, since it geometrically constrains the design of four other sub-systems. Further, the primary element of the prestressed tied rafter should be the top chord (A1), meaning that increased attention should be given to optimising this element and its interfaces to other elements within the sub-system during design. The case study findings support the results obtained from the summation. From the company MD of the case study, the roof system is considered as the most important structural sub-system, since it accounts for 70% of the total cost of a long-span timber structure (table 2).

7. Discussion

In this paper, the DSM was found to be a holistic tool for the systematic consideration of two functional requirements in timber construction design. The considered functional requirements were limited to force transfer for the design of load-carrying capacity and geometric constraints for construction site assembly. Using a 3-D DSM hierarchy, figure 5, this method has the potential to similarly model multiple functional requirements, e.g. requirements on the fire resistance or long-term durability of the timber material subjected to environmental loads. For the long-span timber structure the modular division of the structural system into sub-systems provided the standardisation of interfaces that resulted in constructability during assembly. The DSM express the structural system modularity by providing a standardised system view, i.e. a holistic system view (structural DSM in figure 6), a detailed element view (sub-system DSM in figure 7) and physical and functional interactions among elements and modules using the 3-D DSM hierarchy, figure 5.

The DSM can aid in detailed design and production management by using simple matrix tools. In this paper, summation was used as an example where the importance of structural sub-systems and components was evaluated based on the integration of structural design (force transfer) and assembly (geometric constraints) considerations. It was argued that a high number of requirements on part of a system indicate the need for increased attention during design, as supported by the case company MD who primarily designs long-span timber structures according to its cost. Using the proposed “design sums” in table 3, it is therefore possible to order every sub-system or element by importance. However, if more or other functional requirements such as fire and sound
insulation are included in the DSM modelling, it is unclear that summation would be a satisfying evaluation criterion; instead other (more complicated) evaluation criteria would have to be developed and tested.

As stated in the introduction, the primary use of the developed method was not aimed at structural design. Rather, the purpose of the developed DSM method was to identify constructability obstacles between structural design and on-site assembly and thus eliminate waste. Constructability was argued as an important factor in the elimination of waste and the realisation of an industrialised construction process. The practical possibilities of DSM modelling for constructability and waste elimination are discussed in table 4. The discussion provided in the table is based on experiences obtained from case study results presented in this paper and the multi-storey housing case study presented in Björnfot and Stehn (2005). As an example from table 4, the designer is the construction participant who provides the products with physical properties subject to customer demands. To provide constructible solutions, design work in construction requires close cooperation with the manufacturing (manufacturer) and assembly (contractor) processes. DSM modelling is able to provide the designer with geometric constraints as demonstrated in this paper. Tolerance considerations can be similarly modelled, i.e. by either including them in the geometric constraints as quantifiable numbers or modelled as a separate DSM layer.

This paper only presents the initial method development. Future possibilities of the DSM modelling for constructability work and waste management were discussed in table 4 and considered relevant in a timber construction context based on previous work by the
authors (Björnfot and Stehn 2004, Björnfot and Stehn 2005). However, more case studies and research are required to generalise and validate the method. At least one more functional requirement (e.g. fire resistance, sound insulation, etc.) and other types of housing (timber frame systems, detached housing, etc.) should be modelled and tested. Based on the relative ease of modelling the force transfer in this paper, the authors believe that this task is possible using the DSM hierarchy presented in figure 5. Instead, the main question then becomes, ‘How can such a method be developed for use in practice?’ The straightforward answer to such a question would be to develop a computer based system. However, if such a computer system is to be accepted by the construction industry, the information requirement for constructability and the issues that can occur if this information is not transferred must be understood and accepted (Fischer and Tatum 1997).

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References


Product design for improved material flow – a multi-storey timber housing project

By: Anders Björnfot and Lars Stehn

(The paper has been edited to fit this thesis format, but the contents remain the same)

PRODUCT DESIGN FOR IMPROVED MATERIAL FLOW
– A MULTI-STOREY TIMBER HOUSING PROJECT

Anders Björnfot¹ and Lars Stehn²

ABSTRACT
Understanding of construction has evolved to include a deeper understanding of its mechanics; in addition to traditional on-site work involving the manufacturing of building products – industrial construction. One of the most important aspects of any industrial process is flow of materials and resources. Using empirical data from a unique multi-storey timber housing project, this paper aims at building a better understanding of how product design affects flow of materials in housing construction.

Even though a high degree of prefabrication was used in the project, the amount of complementary site work caused delays, complaints, and a slow learning cycle. A standardization process was used to shift product ‘know-how’ from person to product, resulting in increased flow and a reduction of errors. Prefabrication was not the sole solution to the encountered problems, but the controlled and ordered environment in prefabrication provided solutions at early stages.

Instead of working towards solving the main production issues, the management was instead observed working with minor changes (first-aid solutions) to control flow. If industrialized multi-storey timber housing construction is to be successful, product design decisions should be thought through, thoroughly, from start to finish using standardization as a guiding star.

KEY WORDS
Assembly, lean construction, logistics, multi-storey timber housing, prefabrication, standardization.

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INTRODUCTION

The understanding of construction has evolved to include more than on-site, traditional construction work. Construction now includes a deeper understanding of its mechanics, in addition to on-site work, involving the manufacturing of products – referred to as industrialized construction (or simply industrial depending on the context used). The activities involved in manufacturing and on-site assembly are in theory structured under the terms factory and construction physics (Bertelsen, 2004). This new understanding has provided terms to describe and control processes and operations in order to bring a construction product to life, e.g., waste management, work structuring, industrial operations, etc. One of the most important aspects of any industrial process is flow of materials and resources (Bertelsen and Koskela, 2004).

The design of building products (floors, walls, etc.) has an important impact on flow, evident from one of the main construction issues - lack of tolerance consideration from early design, to manufacturing, and construction site work (Tsao et al., 2004). Solving flow issues already at the product design stage was in Björnfot and Stehn (2004) argued as the main path towards leanness in housing construction. Using empirical data from a unique multi-storey timber housing project, this paper aims at building a better understanding of how product design affects the flow of materials in construction. Since this paper contains the early stages of the case study, no quantifiable aspects of flow have been collected. Instead, the aim is to explain the observed events in a lean construction context. The purpose of this paper is to analyze current practice of product design in a Swedish multi-storey housing project, and to discuss product design strategies for improved flow. Of interest in this paper is therefore to identify processes, or activities, where lack of flow is a problem, and also to propose solutions to these problems.

CONSTRUCTION THEORY AND TERMINOLOGY

Understanding of construction has with the onset of lean construction evolved into two ways of thinking; factory and construction physics (Bertelsen, 2004). Factory physics is an understanding of construction as a controlled and ordered system where construction products are manufactured under factory conditions and assembled on-site using industrial operations. Construction viewed from site dynamics is far from such a controlled and ordered system. Construction has in recent literature been denoted as complex and chaotic, e.g., uncertainty in production labour productivity (Radosavljevic and Horner, 2002), project network fragmentation (Dubois and Gadde, 2002), etc. These construction ‘peculiarities’ are well known issues in construction research today. Construction physics is the understanding of these specific dynamics. In this paper, construction physics is used to denote work and activities performed to maximize value and remove waste on the construction site. Figure 1 illustrates construction and factory physic, and their relation to the main construction phases; this way of understanding construction is in accordance with the ‘Transformation-Flow-Value theory’ (e.g., Bertelsen, 2002). The decoupling point (DP), see also Naim and Barlow (2003), signifies a change in thinking for the completion of a construction project, i.e., this is where the
characteristics of construction changes from factory to site based production; the further
downstream the DP is pushed, the less amount of work is performed on site while the
factory production increase in importance. Consequently, increasing the amount of
industrialization in a construction project is achieved by manufacturing more under
factory conditions, and/or using industry operations and tools for on-site work.

![Figure 1: Understanding of construction as a combination of factory and construction physics.](image)

Lately, industrialization as a concept has been addressed in construction research (e.g.,
Crowley, 1998; Stehn and Bergström, 2002; Björnfot and Stehn, 2004). The importance
of prefabrication and pre-assembly for industrialized construction is described in
literature (e.g., Gibb, 2001; Ballard and Arbulu, 2004). Tools used to manage work under
factory physics are well developed in the manufacturing industry; one example is
Enterprise Resource Planning (ERP) tools. In Sweden such tools are being developed for
use in manufacturing of timber frame housing (Bergström and Stehn, 2004). Following
the introduction of lean thinking in construction, tools for industrial site work are more
frequently discussed in construction literature; the Last Planner system (Ballard, 2000),
and work structuring principles (Tsao et al., 2004) are but two good examples.

Work structuring and tools for industrial site work, as well as industrialization
involving prefabrication and pre-assembly, aim at the core of lean construction, namely
value generation, removal of waste, and improved flow. The seven traditional wastes of
construction (overproduction, correction, material movement, processing, inventory,
waiting, and motion) and the 8th waste (make-do) are given in Koskela (2004). During a
construction project, many participants are involved expecting value generation; tenants’
desire satisfying living quarters, contractors desire return on investments, etc. Value is
therefore hard to measure in absolute terms; value for one participant is not necessarily of
any value for another. The relationship between value, waste, and flow is by the authors
summarized as; if an activity, product design, or process hinders flow, then in some sense
it provides less value while generating waste. Waste can be identified by locating flow
bottlenecks. Flow charts can be used to identify waste and flow bottlenecks, e.g.,
improvement of a house-building supply chain (Naim and Barlow, 2003), and study of a
module production system (Arbulu and Ballard, 2004). A flow chart is in this paper used
to study the multi-storey housing project.

CONSTRUCTION PRODUCT GENERATION

As the materials are transformed into building products, the value of the product grows.
When the product achieves its final place in the structure and is ready for end customer
use, the product has attained its maximum value. Figure 2 illustrates a general example of how value is generated in a multi-storey timber structure. Each product involves the use of upstream products, e.g., raw material (timber, plaster, etc.) convey no direct value to the structure by itself, but is in the form of elements (processed raw material), required for downstream products. The highest order of product value in construction is volumes (ready-to-use living space). In this paper, this scenario is called the ‘product value chain’, where value generated is comparable to both streamlining processes (process value) (Starbek and Menart, 2000) and value generated for the end customer by customization (Naim and Barlow, 2003). A Swedish study of the domestic housing industry indicated a higher return of asset for volume-product companies compared to traditional element companies (Bergström and Stehn, 2004). If return of asset is considered a value for a company, then volumes clearly provide Swedish manufacturers with a higher value than element or module production, as illustrated by Figure 2.

Figure 2: Product value generation in multi-storey timber housing construction.

Element and module manufacturers produce products in factories, which are then transported to, and assembled on, site. Volumes are produced through element manufacturing, which are then assembled to three-dimensional volumes complete with installations, surface finishing, doors, wardrobes, etc. The volumes are then transported to the construction site, assembled, and remaining fixed equipment is added. Housing construction using volumes is thus highly dependent on the factory side of construction, which in Figure 1 would push the DP downstream. The design and value generation for each structural component in housing construction can be described using the terminology of Figure 2. Figure 1 can then be used to describe how industrialized the production is and what form of improvements would provide most value for its completion – factory or construction.

In this paper a floor structure is used as a case example. The floor structure is a module built-up from multiple elements and sub-assemblies, integrating many technical systems – i.e., joists or slabs for load-carrying, ducts and cables for installations. If the floor structure is manufactured as a module, then the demand on manufacturing is high (the DP moving downstream). If the floor structure is manufactured as sub-assemblies then the on-site assembly process will increase in importance (the DP moving upstream).

CASE STUDY: MULTI-STOREY TIMBER HOUSING PROJECT

A multi-storey timber housing project is studied, Figure 3. An interesting aspect in this case study is the material and structural system choice, massive timber elements in both
floors and walls, Figure 4. Before 1995, multi-storey timber structures were prohibited due to restrictive Swedish fire regulations. Consequently, there is presently a lack of timber construction knowledge among Swedish contractors, consultants, engineers, and architects. The uniqueness of the case is further amplified as product development and experience feedback has progressed hand-in-hand with actual construction.

The multi-storey timber housing project involves five buildings of six floors each (a total of 95 apartments over 8,600 m² [≈ 93,000 sq. feet]). The case study involves the construction of the first three houses (numbered 1 to 3 in Figure 3). The project is a design-build project where the main contractor procures suppliers, consultants and other contractors. Practical experience was obtained from personnel responsible for design and handling, i.e., interviews with construction workers, site supervisor, project management, and manufacturer personnel. Other data used was documentation from manufacturing and assembly. The main interest during the interviews were collecting experience of floor structure handling and assembly; what are the main problems encountered using the current design of the floor structure, and how can the design be improved to ease flow?

CASE STUDY RESULTS

The floor structure, Figure 5, consists of load-carrying system (massive timber slabs, and T-joists), floor (slabs are used as finished floor surface), and sub-ceiling (a three layer cross-work of timber beams, insulation, and two layers of plasterboards). The product design and material flow results are summarized in a flow chart, Figure 6. The flow chart, illustrates work done under factory conditions and construction site work. Length of flow arrows is just a form of illustration and has no relation to any measure. Value generated (compare with Figure 2) is evident by following the flow (arrows) from Timber to Finished Floor (raw material to module). The DP for this project is identified as the state when the floor structure arrives ready to be assembled on the construction site.

MANUFACTURING

The manufacturer is one of northern Sweden’s largest sawmills and one of Europe’s leading and most modern glulam producers. For the manufacturer, the current project is a
breakthrough for a new technique and a new way of thinking concerning construction using massive timber elements. Due to the low use of massive timber elements, it is only recently they upgraded their factory production to include a higher degree of automation. The decision to move towards more automation was by the manufacturer crucial to secure delivery for the current project. The contractor project manager stated; “the manufacturer advertised an undeveloped product, not ready for use in a construction project. They were in belief they were contracted as suppliers only, when they had clearly been contracted with overall responsibility for their products (manufacturing to assembly).”

The manufacturing process has been constantly streamlined during the project. Today, manufacturing of the floor structure is performed in a semi-automatic process using computer aided machinery, and classic construction work, Figure 7. The manufacturing processes (Make MT to Form Module) are described in Figure 6 and Table 1. Timber required for manufacturing of elements and T-joists are brought straight from the manufacturers own sawmill and stored at the factory. The installation work is performed by a contracted installation crew. Cutting and notching the elements is done in a computer aided machine (Cut 1). The manufacturer factory supervisor stated; “the CNC machine provides the slabs with measures according to provided drawings. Tolerance mistakes are mainly due to errors in the detailed design stage.”
Table 1: Description of the processes used in the floor structure flow chart (Figure 10).

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<th>Process</th>
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<td>Make MT</td>
<td>Massive timber elements (width: 1200 mm [≈ four feet]), are fabricated using three to five glued cross-laminates. The fabrication process is similar to the manufacturer’s fabrication of glulam, which is well known and used within the company for a long period of time.</td>
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<td>Cut 1</td>
<td>Using a CNC machine, the elements are provided dimensions according to drawings, and sockets for installations and sanitary areas are cut. Tolerance problems emanating from this stage are reported as uncommon.</td>
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| Form 
  element | Glulam beams are glued to the massive timber elements forming beams with T-shaped cross-sections supporting the massive timber elements. The formed elements are then glued together two and two forming elements up to a width of 2400 mm [≈ eight feet]. |
| Cut 2     | Holes and notches are cut into the beams for installations. This work is currently performed by hand using handheld machinery. Handwork is prone to human error, and tolerance errors have been reported from this stage. |
| Form 
  ceiling | A cross-work of timber is formed to support and make room for the sub-ceiling. “Blocks” of timber are added to support the modules in transportation. |
| Form 
  module | Plasterboards are added to the pre-cut elements, while drains and ducts are added by specialised installation contractors. A layer of insulation is added before the ceiling is assembled, producing a module ready for shipping and on-site assembly. |
| Assembly  | The modules are assembled straight from trailers, using a tower crane. The modules are joined to walls using steel-plates and nails or screws. After assembly the ceiling is cut lose from the floor. Tolerance errors discovered at this stage was identified as related to human errors in detailed design or fabrication. |
| Finish 
  ceiling | On-site the sub-ceiling is complemented; A layer of timber is attached, cables for sprinkler and electricity are added by installation contractors, and then insulation and two layers of plasterboards are added. All work is performed from below. At this stage, installation tolerance issues have been the main concern. |
Assembly problems related to manufacturing has been most common during assembly of the first house, the manufacturer factory supervisor stated; “at the start of house one, we had problems with efficient manufacturing of the floor structures, since it’s a new product for us and we didn’t have a fully developed manufacturing process.” These errors are mostly related to the massive timber elements having the wrong dimensions, therefore requiring extra cutting work on site, resulting in assembly delays. The numbers of errors related to manufacturing were substantially reduced for house two and three, as shown in a register of construction site faults maintained by the contractor site supervisor.

Another common error related to manufacturing is the cuts and notches used for complementary site work on installations – a general consensus among the site workers are; “the cuts and notches are much too small for reasonable work rate, and low tolerances on notches makes it very difficult for us to uphold the strict demands on fire and sound insulation. It is not uncommon that the ducts and pipes assembled at the factory are placed up to a few decimetres from their intended place.” Feedback between site workers and factory workers have solved many of these issues, though there are still, as of house three, complaints regarding installation work on site.

LOGISTICS AND HANDLING

The assembly of the floor structure for a whole floor is performed in two stages during two sequential days. Approximately half the floor is assembled in each stage. The manufacturer is responsible for transporting the floor structure modules to the construction site. The modules for each assembly stage were supplied just-in-time using one truck and trailer; the transports were pulled from the factory by the assembly schedule. This has been carefully organised in detailed design to minimize transportation, the manufacturer factory supervisor stated “we have worked with a limit for the height of the modules to ensure they can be delivered to the site on one truck and trailer. This is the main reason why not more parts of the sub-ceiling are integrated already at the factory.” The off-loading was supervised by four workers and a tower crane, one worker connects the modules on the truck (using straps as shown in Table 1 – Form Module) and the remaining three assemble the modules. “The transportations and off-loading of modules has worked as intended for all three houses” is a general consensus among all involved parties. Though, the straps used to off-load the modules are problematic, since these have to be removed and the holes must be carefully insulated to cover sound and fire demands.

At the beginning of this project (house 1), none of the contractor work crew was familiar working with massive timber floor structures integrating structural system and sub-ceiling. The only know-how of the system was in the hand of the manufacturer’s personnel. Therefore, the manufacturer factory supervisor was initially forced to spend time teaching the work crew how to handle the new system. The supervisor spent a total of six weeks (three assembly cycles) on site transferring his knowledge to the work crew. This enabled feedback of notches, tolerances, connectors, etc. to be brought back directly to manufacturing. All construction site personnel agreed that “the manufacturer factory
supervisor’s role was critical for the success of this project. Without his aid we would still be standing out there trying to understand the drawings.”

**ASSEMBLY AND COMPLEMENTARY WORK**

The structural assembly of each floor was performed during a nine day assembly cycle. The modules were fastened on the walls using steel-plates with nails or screws, Figure 8. Handheld machinery (most common; nail guns) was used for the fastening operations. Screwing was, when possible, preferred over nail guns by the site workers due to safety reasons and noise. With the floor structure assembled, complementary sub-ceiling work was performed; adding the third and last layer of timber to the sub-ceiling cross-work, followed by electricity and the sprinkler system (Table 1 – Finish Ceiling). Then, missing insulation and plasterboards were complemented.

In assembly, the drawings have been difficult to understand, as was also the case in logistics and handling. The expertise of the manufacturer factory supervisor helped solve many of the issues with the assembly cycle. During early assembly, the fit between factory and on-site assembled installations was an issue. Direct feedback between site workers and the manufacturer factory supervisor solved many miss-fits in installation work, Figure 9. One of the most problematic assembly operations was the connection between floor modules and walls. These operations were commonly complained upon, it is by the site workers often stated that “a smarter way of fastening the modules is a must; the way we have to work now is simply not possible in the long run.” Even though the assembly process has been continuously improved from house one to three, the assembly schedule has remained mostly untouched. It was agreed on that assembly could be made faster, but the site workers expressed a need to have plenty of time for assembly work due to the rigorous demands on connection work still remaining.

The complementary work on the sub-ceiling is pointed out as an important issue, both from a work environment, and a technical perspective. Complementary work on installations is problematic, as one site worker expressed; “there is very little space to work in and the tolerances allowed are minimal, best would be if complementary work on installations could be minimized by prefabrication.” Often asked for by the site crew is pre-assembled plasterboards. No reason for not integrating plasterboards in factories was given by the interviewees. Assembly of plasterboards in factories would circumvent another issue, storage on site. For this project the plasterboards for both walls and sub-ceiling are stored at their place of use within the houses. Due to limited space, the plasterboards are often a hindrance when performing complementary work.
DISCUSSION AND CONCLUSIONS

As shown in Figure 6, lean construction theory involving factory and construction physics was successfully used to describe the observed production events. Due to a general lack of timber construction knowledge among Swedish construction participants (Björnfot and Stehn, 2004), Swedish multi-storey timber housing projects are often prone to flow bottlenecks and waste generation. This project is no exception. Even though a high degree of prefabrication was used (modules), the high amount of complementary site work caused delays, complaints, and a slow learning cycle. These issues stress the importance of construction physics considerations in prefabrication decisions. In this project, it is clear that the design of the floor structure had a large impact on material (and resource) flow. Table 2 presents examples of product design observations obtained from the case study, highlighting the importance of careful product design.

Table 2: Examples of performed product design actions for improved flow.

<table>
<thead>
<tr>
<th>Problem</th>
<th>Performed Action</th>
<th>Improvement in Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cut 1</td>
<td>Even using CNC, poor design documents lead to elements delivered to site with wrong dimensions.</td>
<td>More attention was given to manufacturing and tolerances already at the detailed design stage.</td>
</tr>
<tr>
<td>Cut 2</td>
<td>Handwork using standard handheld machinery is prone to human errors and mistakes, which are especially evident in complementary site work.</td>
<td>Site installation workers have been in close contact with factory installation workers and manufacturer factory supervisor.</td>
</tr>
<tr>
<td>Assembly</td>
<td>The drawings are difficult to comprehend, and the amount of plates and fasteners used cause bad work conditions and parts missing in assembly.</td>
<td>In the design stage the number of steel-plates and fasteners required for assembly was significantly reduced.</td>
</tr>
</tbody>
</table>

It should be noted that neither of these performed actions had any major impact on the flow chart structure (Figure 6), i.e., the relation (amount of work) between factory and construction physics is unchanged. Even with the performed actions, the main issue related to the sub-ceiling remain, i.e., complementary work from below. The performed actions instead served as a means to remove waste resulting in improved flow within, and between, processes (in Figure 6 this improvement is not quantifiable). More fundamental actions are required to fully benefit from the prefabrication. Table 3 proposes solutions to two of the main identified product design issues and their expected impact on flow.

The Finish Ceiling solution would induce a major change in the floor structure flow chart; division of the floor structure into floor and sub-ceiling, Figure 10 (the processes before Cut 2 are omitted for visibility). In contrast to the flow chart used in this project (Figure 6), the empirical data suggests a flow chart where the DP is moved even further downstream, indicating more work under factory conditions and assembly being the only remaining site activity. While moving work from the site to factories would ease
assembly, manufacturing and logistics would instead be introduced with an increased workload. Prefabricating more is not the sole solution to all problems in this project. But compared to the variability of site production (Bertelsen, 2002), a holistic product design where more of the product completion is performed in factories would provide a controlled and ordered environment with opportunities to solve site waste generation issues already at an early stage.

Each problem identified, and each proposed solution, is a standardization process to continuously improve the floor structure by removal of waste and improvement of flow. Continuous improvements are an important part of lean thinking, and are usually integrated with innovation strategies (Knuf, 2000). All encountered problems can be identified as traditional construction wastes; the main waste in this project being corrections. Each action to solve these problems serves as a driver to shift product knowledge from practitioners to product. This shift of knowledge is important in standardization processes; buildability/constructability is a good example of where standardization serves as a driver for site productivity (Björnfot and Stehn, 2004). The initiator for the shift of knowledge in this project was the manufacturer factory supervisor. Know-how transferred to the construction site workers eventually resulted in an understanding of handling and assembly.

Table 3: Examples of remaining product design issues and proposed solutions.

<table>
<thead>
<tr>
<th>Problem</th>
<th>Proposed Solution</th>
<th>Expected Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assembly</td>
<td>Fasten the steel-plates to the modules already at the factory, and find an innovative way to connect these to walls on the site. The steel-plates can also be designed to serve a purpose in off-loading of modules.</td>
<td>Prefabricating and finding innovative connections would significantly reduce re-work on site. Possible problems encountered are related to transportation, storage, and handling of elements containing jutting steel-plates.</td>
</tr>
<tr>
<td>Finish Ceiling</td>
<td>Divide the floor-structure in two parts; floor and sub-ceiling. If the sub-ceiling is assembled first, this enables work to be performed from above. This would also enable the whole sub-ceiling to be prefabricated.</td>
<td>Working from above is a preferred working position and provides increased quality in complementary work if required. Problems are related to manufacturing, which may be difficult handle due to reduced stability.</td>
</tr>
</tbody>
</table>
The manufacturer site supervisor was the coordinator continuously improving the work and design of the floor structure, while the construction site workers provided input for the standardization of the product and process, Table 2. The proposed innovations (Table 3) were mainly provided by the project management and the manufacturer factory supervisor. Figure 11 illustrates the participants’ roles in product development for this project. In each row, the relative area of each process (standardization, continuous improvements, and innovation) illustrates the amount of work performed by the participants. A better developed floor structure design would have allowed the management to give more attention to finding innovative solutions, instead of developing first-aid solutions to make it work at all.

![Diagram showing roles of participants in floor structure development process.](image)

Figure 11: The manufacture’s and site personnel’s roles in the floor structure development process.

Concluding this paper, the results highlight the importance of the DP for industrialized construction. Failure to utilize a holistic process view in prefabrication often ends up with problems, i.e., unnecessary complementary site work where the advantages of prefabrication are lost. The project has to live with the initial prefabrication decision – changing a prefabrication strategy on the run is often difficult due to long lead times (Koskela, 2003). The main observations in this case study are summarized as;

- **Think holistic.** The substantial complementary site work in this project is a result of poor product design decisions in early design phases. As a result, the main advantages of prefabrication (control and order) are lost. Product design decisions should be thought through, thoroughly, from start to finish. In this project first-aid solutions was employed to improve flow but the main issues still persisted.

- **Standardized thinking.** In this project each module could have varying dimensions, resulting in unnecessary lead times in fabrication and errors in assembly. The findings indicate that prefabrication without a ‘standardized way of thinking’ (more related to mass customization than mass production) is prone to issues; obvious from the managements’ decision to add part of the sub-ceiling to the floor, without realizing the amount of added work in site assembly.

The above points are not new to the construction community; still failure to utilize these facts is all too often documented. In this project the management, responsible for setting
fundamental changes into motion, was instead observed as working with minor changes (first-aid solutions) to control flow. The main reasons for this are most likely related to a combination of using a relatively new product, participants not used to working together, and a paced time-to-finish without time for any changes during production. But these conditions are apparently more of a rule than an exception in construction.

ACKNOWLEDGEMENTS

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REFERENCES

PAPER III

Application of Line-of-Balance and 4D CAD for Lean Planning

By: Anders Björnfot and Rogier Jongeling

(The paper has been edited to fit this thesis format, but the contents remain the same)

APPLICATION OF LINE-OF-BALANCE AND 4D CAD FOR LEAN PLANNING

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Abstract

This paper suggests the application of the Line-of-Balance scheduling technique in combination with a 4D CAD workspace model as a method to improve the management of the flow of resources through locations in construction projects. Current scheduling methods fail to consistently manage work flow. The lack of work flow planning can disrupt the construction process, leading to waste. The proposed methods are applied to a case study of a multi-storey timber housing project. It is shown that many of the problems experienced in the actual construction process, quickly become evident from an analysis of a relatively simple Line-of-Balance schedule. Furthermore, the 4D CAD model, used to visualize the flow of work during construction, provides additional insight in the scheduling of construction activities, such as work space availability and partial overlap of work spaces. In the article we refer to the guiding principles from lean construction in relation to virtual design and construction methods, such as simulations with 4D CAD. Additional research and studies of practical applications are suggested to facilitate the combination of principles from lean construction with virtual design and construction methods.

Keywords

Line-of-Balance, 4D CAD, construction planning, timber housing construction, work flow
1 Introduction

Multi-storey timber housing construction has in recent years seen an increase in use on the Swedish construction market. There are currently a number of construction methods available for these types of buildings, ranging from traditional methods to prefabrication using elements and volumes. Production of multi-storey timber housing often involves the use of both factory and on-site production. Factory production of timber housing components and prefabricated houses are well-developed in Sweden by utilizing automated machinery and process control systems. On-site timber frame construction is not developed to the same degree, leading to an inefficient on-site construction process (Björnfot and Stehn, 2005).

Some of the problems related to on-site construction are directly caused by a deficient design process and poor prefabrication strategies, which commonly results in inefficient work operations and difficulties to control the work progress (Björnfot and Stehn, 2005). In addition there are a number of problems (e.g. rework, quality issues, delays, forced production) that are directly, or indirectly, caused by poor planning and insufficient control mechanisms of the construction process. Insufficient planning in addition to deficient product design may lead to work flow uncertainty and increased variability of crew productivity, possibly disrupting the construction process (Tommelein et al., 1999).

A recent Swedish study of non-value adding work on the construction site indicated that up to 35% of work performed is waste, e.g. waiting, rework, movement (Josephson and Saukkoriipi, 2005). Hence, there appears to be a great potential to improve the flow of resources through locations in construction projects. Improved planning methods for work flow (the flow of resources, such as crews and materials through locations in projects) can make the flow of resources more reliable and continuous through the construction site. Improved work flow reliability provides a more efficient production process, less wasted effort and rework, and better matching of resources to tasks (Ballard, 2000). Planning and control over construction operations and a design process taking constructability issues into consideration are necessary steps in improving quality and productivity of the construction process.

1.1 Aim and scope

The aim of this paper is to evaluate the application of two increasingly used process design methods for improved planning of construction operations in a case study project. The first method is the Line-of-Balance (LoB) scheduling technique that is used to evaluate the construction planning of the case study project from a work flow perspective. The second method concerns simulation with 4D CAD, which is used to analyze the flow of scheduled construction operations through work locations of the case study project.

The paper first introduces the LoB scheduling technique and 4D CAD simulation after which both methods are applied to a multi-storey housing project. The article continues by discussing the benefits and limitations of both methods, based on results from the case study. This section is followed by a discussion of the benefits of the combined use of
scheduling and simulation with LoB and 4D CAD. The paper concludes with a discussion and suggestions for further research.

2 Production planning and simulation

All events during a construction project cannot be perceived by planning alone. However, relevant planning of resources and activities can allow complex projects to be brought under control (Kenley, 2004). Control of activities (i.e. work tasks), trades (i.e. work teams and subcontractors), and resources (e.g. machinery and tools) on the construction site is of vital importance for the management of site production in construction (Heinrich et al., 2005). Construction planners need to carefully design a process that ensures a continuous and reliable flow of resources through different locations in a project (Jongeling et al., 2005). The flow of resources through locations and the resultant ability to control hand-over between both locations and crews, greatly empowers the management of construction from the perspective of day-to-day management of activities (Kenley, 2004).

2.1 Managing production through Line-of-Balance (LoB)

As a scheduling tool, LoB has its origin in the manufacturing industry where it has been successfully used for a long time to plan and control repetitive one-off projects (Heinrich et al., 2005). The resource oriented LoB technique has also been developed for the construction industry, but has often been disregarded in favor for the activity oriented Critical Path Method (CPM) developed as an extension of the Gantt/bar chart (Heinrich et al., 2005). Only recently, with the development of LoB for commercial use in Finland (e.g. Soini et al., 2004), has the technique been reborn and is now considered, by some academics, as the future in construction planning and management (Kenley, 2005). In practice, LoB has mainly been used for projects with a large degree of repetition over a relatively small number of discrete activities (Heinrich et al., 2005). However, LoB has also been successfully used on large scale projects in Finland (Soini et al., 2004).

LoB is a specific type of linear scheduling method that allows the balancing of operations such that each activity is seen as being continuously performed, even though the work is carried out in various locations (Heinrich et al., 2005). Scheduling with LoB is oriented towards the required delivery of completed units and is based on knowledge of how many units must be completed on any day so that the programmed delivery of units can be achieved (Arditi et al., 2002). LoB considers location explicitly as a dimension which allows for easier planning of continuous resource use, which in turn enables cost savings, cuts in project duration, reduced work flow variability, and less schedule risks as subcontractors crews can be kept on site until their work is finished (Soini et al., 2004).

Scheduling a project with LoB begins by breaking down the project in physical sections (i.e. locations), such as for example ‘location 1’ included in ‘building A’, which is part of ‘project X’. Creating tasks in the schedule (i.e. lines) is done by using items from the bill of materials or cost estimation in a project. For example, from the bill of quantity item ‘floor elements’ the following tasks are derived: assembly of floor element,
finish ceiling and finish flooring. In this way a specification is made for the amount of work per location in a project for a construction crew. Based on these quantities and task description, the required crew size can be determined. The bill of quantity items and cost estimation define what should be done and the tasks in the LoB schedule define how this is done. This relation is often not explicitly made in CPM schedules and when done so it leads to very detailed and unmanageable schedules (Huber and Reiser, 2003).

Figure 1 shows the most common deviation types that can be identified by using LoB diagrams (Jongeling and Olofsson, 2006). These deviation types indicate scheduling mistakes and opportunities to plan for a stable and continuous flow of work through locations of a project. The two main principles used to minimize the deviations and to plan for continuous work flow with LoB diagrams are synchronization and pacing. Synchronization concerns the effort to achieve a similar production rate for all activities. A synchronized schedule can be identified by parallel lines (i.e. parallel tasks) that show a constant time-space buffer between different tasks. Pacing means that the activities are scheduled to continue from one location to another without interruptions.

![Figure 1](image.png)

**Figure 1**  
*Left: Line-of-Balance diagrams showing common deviation types. Right: Typical solutions to these deviations. Locations are represented on the Y-axis and project time on the X-axis. (Jongeling and Olofsson, 2006)*

The LoB technique entails useful mechanisms for the planning of work flow. However, the LoB technique does not explicitly address the spatial configuration of activities. In order to identify what part of a building is related to an activity, users have to use 2D drawings to understand the spatial implications of an activity. Combining LoB with 4D CAD could add spatial insight in construction planning that could improve the quality of the process design.
2.2 Simulation and visualization using 4D CAD workspace models

4D CAD models allow project participants to simulate and analyze what-if scenarios before commencing work execution on site (McKinney, 1998). Common for projects using 4D CAD is visualization of design decisions and improved communication of these decisions in the design phase (Woksepp et al., 2005). Based on Japanese experiences, Nakagawa (2005) illustrates the importance of visualization for the maintenance of a synchronized and paced work flow and for the implementation of Lean Thinking in construction. Construction site workers tend to focus on their own tasks and therefore become indifferent to other related activities which often create waste in the form of rework and errors, particularly in projects with a large number of activities and crews. Proper visualization of overall project progress is encouraging workers to improve their own work and the coordination with other work crews, which facilitates work flow while waste is reduced. Continuous improvement through learning is a fundamental characteristic of Lean Thinking (Womack and Jones, 2003).

4D CAD models are typically created by linking building components from 3D CAD models with activities that follow from CPM schedules (e.g. Koo and Fischer, 2000; Tanyer and Aouad, 2005). Building components that are related to activities that are ongoing are highlighted. The 4D CAD model provides the user with a clear and direct picture of the schedule intent and helps to quickly and clearly communicate this schedule to different stakeholders in a project. 4D CAD models provide planners with a spatial insight in the scheduling process of construction operations which is not provided by using 2D drawings in combination with CPM schedules or LoB diagrams.

The difficulty of applying flow-based thinking in today’s 4D CAD models arises from the fact that these models are based around discrete activities from CPM schedules. In addition, 3D CAD building models, also referred to as Building Information Models (BIM) (Autodesk 2003), on which today’s 4D CAD models are based, do not represent the locations of crews and other resources. As a result, the application of 4D CAD models to model and analyze work flow is limited (Akbas, 2004). Additional 3D components, such as 3D spaces, are needed that can visualize the flow of resources through a project. An advantage of using 3D workspace models is that ongoing activities inside a building can be easily analyzed in contrast to traditional 4D models that are based on 3D CAD building components. In the next section we illustrate how the LoB technique can be used in combination with a 3D space model as an alternative to CPM scheduling for 4D modeling to plan and manage construction operations from a work flow perspective.

3 Application in practice

The empirical part of this paper involves planning and simulation of the construction process of a multi-storey timber housing project using LoB and 4D CAD. Data is collected from a case study of the construction of 95 apartments in five six-storey buildings with basic floor plan according to Figure 2. Floor and wall elements are to a high degree prefabricated and include a load-carrying system, sub-ceiling, installations and covering.
Figure 2  Left: the multi-storey timber housing project (picture by Svante Harström). Right: the basic floor plan of all houses.

We applied the LoB scheduling and 4D CAD method to one of the buildings in the multi-storey timber housing project according to the method shown in Figure 3. First, the LoB diagram was developed from the original master planning of the project. Then, the 4D CAD model was created, based on schedule data and the hierarchical logic of locations. Finally we conducted a comparative analysis of the LoB diagram and the 4D CAD model.

Figure 3  Scheduling and analysis of work flow using LoB and 4D CAD.

The original production plan for the project was performed using Gantt scheduling with a low level of detailing, i.e. production tasks were only scheduled in time with no spatial consideration except for the occasional division of tasks between floors. The original schedule was clearly constructed with a solve-it-on-site mentality which became apparent from observations of actual work performed on the construction site (Björnfot and Stehn, 2005). In our study the original Gantt bar charts was used as input for the LoB diagrams to better understand the flow of resources through locations in the case study project.

The structural design of the buildings was performed using 2D CAD by which all structural elements, installations and interior accessories were detailed. The drawings, over 100 in total, complicated the communication of the design intent and production schedule. Project participants had difficulties in relating the different 2D drawings to one
common view of the project. The level of detail of the installation design was also not sufficient to produce accurate shop floor drawings. We used the available 2D CAD files as a basis to generate a 3D space model of the case study project that we subsequently used as input for the 4D model. The spatial hierarchy of the 3D space model and of the LoB diagram is identical.

3.1 Preparing the Line-of-Balance diagram and 4D model

Scheduling using LoB requires a relevant spatial division of the project. This division should be based on the logic of the work being performed. The spatial logic could not be derived from the available Gantt schedules alone due to the low level of detail. Therefore, the spatial division from the original schedules was supported by field studies on the construction site.

The construction process for the five buildings of the case study project was performed in two stages; assembly of load-bearing structure, and structural and internal finishing work. In the first stage the load-bearing structure was assembled using prefabricated wall and floor elements, Figure 4. This work was performed in a nine day assembly cycle for each floor, beginning with ‘wall linings’, assembly of ‘outer walls’ and ‘inner walls’, and ending with the assembly of ‘floor elements’. The variability in assembly time was large, ranging from about ten minutes up to an hour per element. This was mainly caused by incorrect element dimensions and tolerances due to errors in the design and manufacturing process. These errors resulted in rework on site, e.g. a complete waste of resources. Even though the assembly of the ‘floor elements’ for each floor was generally performed over a two day cycle, a three day span was given to account for the great variance in assembly time. Despite the problems with element tolerances, the assembly of the load-bearing structure was generally considered to be productive and efficient by all participants involved in site production.

![Figure 4] Assembly of floor and wall element on the construction site.

The second stage of the construction process comprised of finishing work. The finishing of the structure included activities such as ‘adjust ceiling’, ‘sprinklers piping’ and ‘HVAC installation’, while internal finishing work denoted activities such as ‘painting’, ‘electricity finishing’ and ‘plasterboard walls’. The production at this stage was
problematic in which numerous design and planning errors became apparent (Björnfot and Stehn, 2005). Even though a high degree of prefabrication was used for the floor and wall elements (e.g. floor elements included installations) a large amount of finishing work was required to complete the elements and finish the building interior. No detailed planning was available for the interior work, due to the fact that these activities were mostly managed ad-hoc on site.

3.2 Production activities and spatial hierarchy

From site observations during production it was found that the spatial work flow for assembly of the load-bearing structure and interior works progressed from apartment to apartment. Based on these observations we divided a building storey into four types of spaces; three apartment spaces of approximately equal size and a common space for staircase and elevator shaft that was slightly smaller, Figure 5. This spatial hierarchy is used in the LoB diagram and 4D CAD model. In addition, 3D workspaces were included to represent activities related to kitchens, bathrooms and service shafts.

![Figure 5](image)

Left: 3D model of the building containing space objects used for 4D simulations. Right: 3D space model of one building storey. Apartments contain spaces for kitchens, services and bathrooms. Spaces for services overlap with spaces for kitchens and bathrooms.

4. Case study results

4.1 Analysis of the LoB diagram

The LoB schedule (Figure 6) is based on the spatial hierarchy in Figure 5 and created with Graphisoft Control (Graphisoft, 2006). A quick look at the LoB schedule verifies the main view from production personnel about the construction process: assembly of the load-bearing structure was efficient while structural and internal finishing work was troublesome. According to the LoB schedule, the assembly process of the load-bearing
structure appears to be reasonably synchronized and paced. In practice, assembly progressed according to the master schedule even though occasional rework had to be performed due to deficient elements. No major delays resulted from the rework since one extra day, serving as a time buffer, was scheduled in assembly of the load-bearing structure.

Execution of structural and internal finishing work was troublesome. Most of these problems were related to the planning of work, where assignments performed by crews from the main contractor and subcontractors were planned daily due to the low level of detail in the construction schedule. Anecdotal evidence from interviews with the workers on site suggests that construction crews were everywhere and it was hard to keep control of what construction tasks were performed, by whom, where and why (Björnfot and Stehn, 2005). Some of this confusion is evident from the LoB schedule where the common planning deviations depicted in Figure 1 were apparent in the case study (highlighted in Figure 6), e.g. crossing of activities, lack of buffers, and activities starting on same day. Deviation type 1, same trade at several locations at the same time, could not be detected in the LoB diagram even though it was apparent from site observations that multiple trades had work-in-process in several locations at once, hindering subsequent trades from performing their work on schedule. With the identified deviations from the LoB diagram in mind, we simulated the construction process using the 4D CAD workspace model to provide additional spatial insights in the construction process.

Figure 6  LoB schedule of the work performed during production. Circles depict possible schedule problems according to the deviations identified in Figure 1.
4.2 Analysis of the 4D workspace model

Activities from the LoB diagram were imported to a 4D simulator (Ceco 2006) in which the 3D space model of the case study project was linked to the schedule data. Different colors were used to distinguish different types of activities and different (sub)contractors. After the linking process was completed the 4D model was simulated and the identified deviations from the LoB diagram (Figure 6) was analyzed, Table 1. In the 4D model, congested work spaces are indicated with a dark grey conflict color.

Table 1 Analysis of deviation types using 4D simulation of the LoB diagram.

<table>
<thead>
<tr>
<th>IDENTIFIED DEVIATION</th>
<th>4D SNAPSHOT</th>
<th>BRIEF ANALYSIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>![Image](181x138 to 528x557)</td>
<td>Two activities are planned at the same time in the same space, indicated by the crossing activities in the LoB diagram and the congested workspace (red) in the 4D model. Synchronization of these activities will improve the work flow through the location.</td>
</tr>
<tr>
<td>3</td>
<td>![Image](181x138 to 528x557)</td>
<td>The LoB diagram shows a conflict on floor 6, but the 4D model indicates that the sprinkler activity is limited to a specific zone, which only partially overlaps work on the roof. Therefore, this conflict does not necessarily have to lead to congestion problems on site.</td>
</tr>
<tr>
<td>4</td>
<td>![Image](181x138 to 528x557)</td>
<td>Several activities start on the same day shown in the 4D model as a conflict (red) on floor 1. The 4D model shows that some of the tasks could start in other spaces on floor 1. This type of congestion can be predicted and avoided using the 4D model and LoB diagram, thereby avoiding unnecessary site management.</td>
</tr>
<tr>
<td>5</td>
<td>![Image](181x138 to 528x557)</td>
<td>The LoB diagram and the 4D model show inefficient use of available workspace on floor 1. At the same time the workspaces on floors 4 and 6 are congested (red). Using the 4D model, a schedule opportunity can be identified allowing for a later start of the subsequent activity, which avoids the identified congestion on floor 4 and 6.</td>
</tr>
</tbody>
</table>
The use of a 4D model in addition to the LoB diagram was, in this case, found to be mostly useful for communication and visualization of the LoB diagram. Most of the deviations could be identified with the LoB diagram alone. However, the spatial context of a number of deviations as identified in the LoB diagram became clearer in the 4D model, compared with representation in the LoB diagram. For example, the space conflict on floor six (deviation type 3 in Figure 6 and Table 1) appeared to concern a partial overlap of work spaces from installation of sprinklers and the roof finishing, which was considered acceptable after viewing the 4D model. Also the flooring activity on floor six could be rerouted later to allow for work on sprinklers and the roof. In addition, the 4D model proved to be of complementary use to the LoB diagram in the process of identifying available work space for congested activities on floors four and six (deviation type 5 in Figure 6 and Table 1). The 4D model also provides a clearer overview of available workspaces compared to the LoB diagram.

Partial overlap of workspaces (deviation type 3 in Figure 6 and Table 1) is a situation that is difficult to manage with the LoB technique. One solution is to use a more detailed spatial division in the definition of LoB location hierarchy. However, this will complicate the planning and management of the LoB schedule. The LoB is based on a well defined spatial sub system, such as a floor consisting of apartments, divided into rooms. This type of static spatial hierarchy of workspaces is not present during all stages of the construction process. The distribution of and boundaries between workspaces is generally much more complex and less clear. Installations of sprinklers are, for example, centered on vertical shafts in the building and do not follow the apartment-based distribution of work spaces. Here, 4D CAD models can be used as a complement to the LoB diagram to provide additional information of spatial irregularities and overlaps in planning and management of construction work tasks.

5. Discussion and conclusions

In this paper the LoB scheduling technique and 4D CAD was applied to a case study of a multi-storey timber housing project. The main strength of the LoB scheduling technique is the possibility of obtaining a synchronized and paced planning of operations, which creates opportunities for construction work to flow unhindered from work space to work space. 4D CAD visualizes the work to be performed, identifying possible space congestions and allowing for more detailed evaluation of different production plans, work methods and design decisions. The main strength of the integrated use of LoB and 4D CAD is the straight-forward evaluation of the feasibility of the production schedule in which users are provided with a powerful set of tools to schedule, manage and communicate project plans. The application of scheduling techniques for work flow was limited to the planning of construction crews through the case study project. For a more comprehensive work flow analysis, we suggest that additional resources that can affect the flow of work are taken into considerations, such as materials, temporary structures and equipment.

By creating a relatively simple LoB schedule (Figure 6) and performing a quick analysis, it was shown that many potential problems quickly become evident, e.g.
possible work space congestion and lack of time buffering. The 4D model provided additional insight in the spatial context of scheduled construction activities. In this paper a 4D workspace model was used to visualize the flow of work during production. 4D models based on spaces are suitable for work flow analyses, but component-based 4D models are required to facilitate for example constructability analysis and supply chain management. A 4D workspace model can in this respect be considered a supplement to the common component-based 4D model. To further improve the feasibility of schedules and to better control the production process, the Last Planner system and specifically the metric Percent Plan Completed (PPC) (Ballard, 2000) can be integrated so that planning can be continuously improved upon through feedback from work execution on site.

Application and integration of LoB and 4D CAD workspace simulations can support the set-up of a balanced and steady work flow in the construction process. The possibility of using the tools for evaluation of schedule feasibility through the visualization of work flow can aid construction in securing constructability. Additionally, the possibility of identifying potential waste and to plan for uninterrupted work flow through LoB and 4D CAD supports the main principles of Lean Thinking (Womack and Jones, 2003); pacing of work at stable productivity levels without interruption promotes quality and learning through continuous improvements, potentially reducing future waste generation (Arditi et al., 2001). Based on the insights provided in this paper, LoB and 4D CAD can be considered two important tools for the increase of efficiency and productivity in the construction industry. We believe that virtual design and construction methods based on principles from lean construction can contribute significantly to the value of the product and the elimination of waste in any construction project. Therefore, more studies are recommended where both areas of research can be combined in the design and construction of building facilities, such as methods for lean design and lean supply chain management.

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Prefabrication: a Lean strategy for value generation in construction

By: Anders Björnfot and Ylva Sardén

(The paper has been edited to fit this thesis format, but the contents remain the same)

PREFABRICATION: A LEAN STRATEGY FOR VALUE GENERATION IN CONSTRUCTION

Anders Björnfot\textsuperscript{1} and Ylva Sardén\textsuperscript{2}

ABSTRACT

Despite a number of attempts to establish prefabrication as a Lean Construction method, there still exists confusion of what prefabrication provides to the management of the construction process. It seems as if prefabrication can provide a means of dealing with value stream fluctuations in highly complex situations, such as a traditional construction project where client value is difficult to accurately define. The prefabrication decision and the strategies for meeting customer demands has been studied for three Swedish producers of prefabricated timber components for multi-storey housing construction.

The case study results indicate that the Swedish construction industry is slowly changing from a traditional project based generation of customer value to offering specific products, adaptable by the customer to suit their own view on value. A prefabrication strategy where a well defined and tested product is offered to customers has the effect of redistributing resources from the design process to the value stream. Such redistribution enables companies with a well developed prefabrication strategy to better control the value stream and to implement new and better ways of meeting customer requirements while continuously improving their work and eliminating waste.

KEY WORDS

Lean Thinking, Multi-storey timber housing, Prefabrication, Product offer, Value generation.

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INTRODUCTION

Bertelsen and Emmitt (2005) promotes the view of construction as a complex system by arguing that the prevailing understanding of construction as an ordered process is completely wrong and that this misinterpretation may be the root-cause of the problems construction management meets over and over again in practice. Under complex circumstances, unforeseen events which completely invalidate the project’s target, planning and approach may occur. These events forces the project team to frequently redefine the project’s basic premises and to make decision based on incremental learning (De Meyer et al. 2002). The reason complexity has been introduced in construction seems to indicate that the nature of construction is beyond understanding and therefore beyond management; especially for on-site construction where the apparent inability of plans to represent reality seems to be a cause for complexity (Kenley 2005).

A possible strategy for controlling unpredictable site conditions is the introduction of an industrialised construction process utilizing prefabricated components (Björnfot and Stehn 2005). Prefabrication, the making of construction components at a place different from the point of final assembly, may lead to better control of the inherent complexity within the construction process (Höök and Stehn 2005). Positive experiences of prefabrication are plentiful, e.g., Luo et al. (2005) state that prefabrication can, if employed efficiently, enable process standardization, shorten lead times, improve quality control, and reduce material waste. Despite a number of attempts to establish prefabrication as a method of Lean Construction in academic circles, there still exists confusion of what prefabrication provides to the management of the construction process.

In this paper, the authors take the initial position that the inability of accurately understanding prefabrication as a strategy for Lean Construction implementation is due to not considering prefabrication in terms of value and value stream improvements (i.e., the first two basic principles of Lean Thinking). It seems as if prefabrication can provide a means (among other Lean methods) of dealing with value stream fluctuations in highly complex situations, such as a traditional construction project where client value is difficult to accurately define. This view is further explored in this paper through a literature review of value generation in construction supported by empirical evidence from three case studies of multi-storey timber housing projects in Sweden.

THE NATURE OF VALUE IN CONSTRUCTION

CLIENT VALUE GENERATION

Construction is a process of delivering value to the client through a temporary production system, which consists of elements shared with other projects (Bertelsen and Emmitt 2005). The client has to make quite a few decisions in the initial stages of the project, e.g., which standards and regulations do I need to consider? Which quality in different parts of the facility do I need? How do I want the facility to look? The client also has to decide on the project budget, a location of the facility, the contractors and consultants who are to be engaged and how they should be organised. It is in these stages the client
defines his value by the specific facility. Clearly, the clients’ task of accurately defining value for the producer seems to be a complex process (Bertelsen and Emmitt 2005).

The actual product definition begins in the initial stages of the construction project. The client has to investigate the prerequisites for the project, specify requirements for the final facility, and estimate its economic consequences. These factors are often dependent on different political decisions executed by local authorities. During the following stages of the construction process, the means for the client to further specify value depends on the organisation of the project execution phase and the involved actors. In Sweden, approximately 35% of the apartments in multi-storey buildings are purchased as design/build projects while 50% are property development projects, managed and owned by a contractor (build-own). In design/build projects, where client value should have been defined in advance, the possibility for the client to further influence the value definition is, or should be, limited while the build-own project by definition permits a larger degree of involvement, i.e., client value is slowly emerging as the end product takes shape.

In construction, value may be divided into external and internal value (Emmitt et al. 2005). External value is the clients’ value and the value which the project should end up with, while internal value is the value that is generated by and between the participants of the delivery team. The external value can be divided into process and product value, where the product value is the actual end product (the facility) and process value is achieved by providing the customer with the best experience possible during the design and construction phases. How the stakeholders in a construction project perceive value is presented as examples of external and internal value parameters in Table 1.

Table 1: Examples of value parameters for stakeholders in construction projects (inspired by Bertelsen and Emmitt 2005, and Cuperus and Napolitano 2005)

<table>
<thead>
<tr>
<th>STAKEHOLDER</th>
<th>PERCEIVED VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EXTERIOR VALUE</strong></td>
<td></td>
</tr>
<tr>
<td>Owner</td>
<td>• Durability</td>
</tr>
<tr>
<td></td>
<td>• Low costs (maintenance and investment)</td>
</tr>
<tr>
<td></td>
<td>• Flexibility</td>
</tr>
<tr>
<td>User</td>
<td>• Flexibility</td>
</tr>
<tr>
<td>Society</td>
<td>• Aesthetics</td>
</tr>
<tr>
<td></td>
<td>• Durability</td>
</tr>
<tr>
<td><strong>INTERNAL VALUE</strong></td>
<td></td>
</tr>
<tr>
<td>Contractor</td>
<td>• Profitability</td>
</tr>
<tr>
<td></td>
<td>• Independence</td>
</tr>
<tr>
<td>Sub-contractor</td>
<td>• Profitability</td>
</tr>
<tr>
<td>Designer</td>
<td>• Independence</td>
</tr>
</tbody>
</table>
The client is often an organization representing three distinct client groups: owners, users and the society (Bertelsen & Emmit 2005). These groups of clients’ value different things at different times during the life of the building, e.g., durability, usefulness, beauty, capital value, flexibility, and environmental aspects. The other construction team members also have values to fulfill, but their main concern should be on delivering the best value to their client whom otherwise would look elsewhere (Emmitt et al. 2005).

In Lean Thinking terms (Womack and Jones 2003), the construction process should be aimed at satisfying customer value (external value), while value for the involved project participants (internal value) should come from continuous improvements and waste reduction endeavours within the value streams. In order for construction to be able to satisfy external value for the customer (e.g., the client), value must first be accurately defined. However, client value can, and in reality does, change over time (Bertelsen and Emmitt 2005) making value management in construction a difficult process indeed.

**DEFINING VALUE – A CONSTRUCTION PECULIARITY?**

Design changes initiated by the client and other stakeholders in a construction project often leads to variability and wasted effort before the changes are implemented and control is restored (Cuperus and Napolitano 2005). For the producers of construction products (contractor, manufacturers, and suppliers) it should therefore be imperative to accurately define customer value before the design process begins. However, based on the multitude of possible client wishes and requirements, and the lack of methods and tools for this purpose available today, it may not even be possible to accurately define value. Construction management involving methods and tools originating from the manufacturing industry has in most cases failed and lead to disappointment. For example, information technology, an everyday tool in manufacturing design and production, has not brought any major benefits to construction; the failure of construction computing is said to be attributed to a deficient understanding of construction (Koskela 2000).

The understanding of production in construction is constrained by the fact that its products and forms of production are different from most other industries. Compared to the production of for example a car, production in construction is considered peculiar in the sense that each product is unique, i.e., construction produces one-of-a-kind products. The main cause for this peculiarity is the fact that the client, i.e., the customer (not necessarily the end customer) who for a majority of construction projects is new and inexperienced with different values that must be fulfilled (Bertelsen and Emmitt 2005). To produce value for the client, the construction process is set up as a temporary production system involving a temporary project organization including all involved participants. The main causes for the temporary organisation is that each time a new building is constructed, the production is set to a new location with new site characteristics and working environments, often involving different contractors based on the client needs and the availability of subcontractors at the location. Not surprisingly, it seems like the client and the way value is considered in construction is a peculiarity in itself, or rather a cause for the perceptions of construction peculiarities. However, again it
is worth stressing that the uniqueness of construction is not extreme from the point of view of production and operations management (Koskela 2003).

The difficulty of defining customer value in construction is apparent but there are ways of facilitating value generation, for example, computer aided design using 3D and 4D CAD are becoming more common (Woksepp et al. 2005), partnering (or concurrent engineering) is once again being brought up as a viable method of defining customer value (Cheng and Li 2004), and target costing is being developed for construction based on its success in the manufacturing industry (Granja et al. 2005). To better plan for and control the delivery of value in construction, improved planning tools such as Line-of-Balance (Kenley 2005) and the Last Planner System of production control (Ballard 2000) has become increasingly popular. However, these methods and tools seem not to, at least by themselves, be able to accurately define value for the client. Rather they seem to be designed with the acceptance that the value stream in construction will fluctuate and the purpose is to eliminate this variability or to dampen its effect. If we accept the fact that the value stream will fluctuate due to the strong influence of the client and the lack of methods to accurately define customer value, then prefabrication can be considered as a strategic method for value stream management.

Prefabrication of construction components is for contemporary Swedish multi-storey housing more a way of how things are done than a question of if prefabrication should be used at all. More and more producers (clients, contractors, manufacturers etc.) of such structures have increased their awareness of the construction process and subsequently increased the level of prefabrication of their production systems. Production of multi-storey timber structures in Sweden has in recent years been performed using a variety of prefabricated components, all from elements up to complete volumes sometimes containing whole completed apartments. The case study results presented in this paper provides a broad view of the use of different prefabrication strategies used on the Swedish construction market and how these strategies facilitate the management of value for the client and other involved stakeholders.

CASE STUDY RESULTS

The first two case studies are part of ongoing extensive research projects with results and analysis presented in other academic publications, e.g., for Case study 1: Björnfot and Stehn (2005), Sardén (2005); Case study 2: Höök and Stehn (2005), Olofsson et al. (2004). Only for Case study three are the results presented not discussed elsewhere. Data collection for all three cases has been performed through interviews, site observations, design and production meetings, and design and production documentation. We refer to the above cited publications for more information on the case study methods utilized. The case study results describe; the company, their product offer, client perceived value, and the prefabrication decision and its effect on stakeholder value.
CASE STUDY 1 – ELEMENT PREFABRICATION

This case study concerns a supplier of prefabricated floor and wall elements based on massive timber slabs for the Swedish construction market, Figure 1. The supplier owns his own sawmill and in addition to producing elements for use in multi-storey housing projects, glulam timber beams are produced for use in other types of construction projects. The supplier strives towards complete prefabrication of the elements, generally including surface finishing, façade and installations. All this work is performed at the supplier’s factory where automated machinery is utilized in combination with traditional construction work. When the elements are completed they are delivered to the construction site and assembled to a complete structural system. The goal of the supplier is to provide a complete system of prefabricated elements, i.e., design, manufacturing, delivery, and guidance for on-site assembly.

The prefabricated element system was recently tested in practice on a multi-storey timber housing project consisting of five houses of six floors each. Due to the material and the element system being relatively fresh on the Swedish construction market, the client decided to procure the contractor under a design-build contract with fixed price to minimize his economic risk. The structural system was procured in the same manner by the contractor, who was promised full responsibility for the design and assembly by the element supplier even though this was the first time this particular system was used in practice. As a result, the system was continuously developed during the project resulting in waste due to rework and delays. This situation was not acceptable to the contractor who, rightfully, was expecting a fully developed system which eventually led to claims on the supplier during production and after completion of the project.

Figure 1: Prefabricated timber floor and wall elements used for multi-storey housing

The main reason it was decided to prefabricate the structural system and integrate as much as possible already in manufacturing was a wish to increase the productivity of site assembly and to guarantee a high quality in on-site work. Site production was already in the conceptual design stage viewed as a possible problem during site production. Since timber is generally susceptible to weather, a “dry construction” process was aimed at through the use of a covering tent (Figure 1). Additionally, use of the tent enabled improved productivity of site production through an assembly type of production process. To facilitate delivery of elements to the construction site, the contractor and supplier
decided to limit the height of the timber elements. However, not surprisingly, this decision resulted in an inability to apply surface finishing and major installations at the factory, later identified as one of the main reasons for the problems in structural and internal finishing work observed in site production.

For this particular project, there was really only one supplier able to deliver elements on such a large scale which lead to the supplier taking on the role of a contractor rather than a supplier of construction components as would have been expected; i.e., the prefabricated element system was as good as designed from scratch for the particular project instead of being offered as a ready system. Clearly, all project stakeholders would have been better off if the prefabricated element system had been fully developed before the project start. This is especially true for the design of installation systems not included in the prefabrication decision, which was difficult to do in advance since initially the elements were continuously being redesigned. Despite all these problems, the prefabricated system was agreed on as advantageous in assembly which progressed according to schedule. However, to become a competitive alternative to other building systems and to increase its market share, further system development is necessary.

**CASE STUDY 2 – VOLUME PREFABRICATION**

This case study concerns a specific Swedish company producing timber frame multi-storey houses for the Swedish construction market. The company projects are run with everything in-house, i.e., they procure land, they design the building according to customer demands, they produce prefabricated volumes in their factories, and they assemble and finish them on the construction site, Figure 2. The company is very much focused on providing customers with what they want while keeping the design and production process as simple as possible. One reason this is possible is that the company own the majority of the value stream by themselves, e.g., they bring subcontractors for installations in-house and uphold long-term relationships with important suppliers.

![Figure 2: Prefabrication and site assembly of volumes including finishing](image)

The company product offer of prefabricated volumes governs the company work in marketing, manufacturing, client negotiations, and on-site production. The volumes are produced through a standardized manufacturing process where wall and floor elements are first produced and then assembled to three-dimensional volumes in the factory. Before
the volumes are ready for delivery to the construction site they are finished with installations, façade, interior surfaces as well as other interior finishing such as wardrobes, cabinets, sinks, and toilets using the companies own workforce or hired subcontractors with long-term relations to the company. Through this work, only minimal finishing work is required on site, i.e., an assembly type of site production is achieved.

The standardized design of the product offer leads to a standardized delivery of the volumes to the construction site, using trucks and trailers. In this manner, the company is able to produce and deliver volumes for projects all over Sweden (a large country in distance if not in size). Before the volumes are delivered, the foundation has already been constructed. While the foundation work is underway, work on the roof is started (which commonly is made out of prefabricated rafters from local producers) leaving only assembly of the volumes, a task performed straight from the trailers using one crane and a local workforce with long relations to the company. Therefore the process of assembling a normal sized house is quick, usually about one days work. When the volumes are assembled, the process of finishing installations and remaining interior commences. Due to the standardized design of the volumes, the finishing process is straightforward and often performed with a minimum amount of wasted effort.

Through the standardized product offer, the company is able to utilize a “simplified” tendering process only including adaptation of the house layouts to the project in question, negotiation of price and date of delivery, and setting up a list of options for the clients’ tenants. Only minor changes of the principle design are allowed to keep a high production-cost efficiency. The client initiates the sales and customization process of the houses when the contract has been signed. When 30 % of the apartments are sold, the start order is given and the detailed design and engineering work commence. From the detailed design phase, design drawings are delivered to the manufacturing process. When production starts, information of selected customer options from the customization process is passed to the construction company in order to individually customize the tenant-owned purchased apartments.

Even though it seems like the company is strict in keeping to its volume production system, they are in reality keen on meeting customer demands. However, client involvement is to a high degree limited to interior and façade design, and add-ons such as balconies. This may seem like a severe limitation in meeting customer demands; however, the customers generally know what to expect from the company product offer and how much involvement they are allowed in design. The volume system has been perceived as limited in flexibility and customization and therefore mostly been used for repetitive standardized housing projects such as student dwellings even though the volume system should be able to cover a larger share of the market. Despite historical setbacks, the company has a firm belief in their prefabrication strategy, striving towards new marketing strategies and better ways of meeting customer demands.

**CASE STUDY 3 – INDUSTRIALISED CONSTRUCTION**

Case study three concerns an innovative effort on the Swedish construction market where the supplier in case study one and the company in case study two has joined forces
together with an architect and construction component suppliers. The aim of this initiative is to increase the involved companies marked shares on the multi-storey housing market, i.e., to produce cheaper houses to a larger market segment than the companies can do by themselves. Even though the case has not been seen in practice yet, a discussion of its prefabrication strategy and customer value generation is of relevance to this paper.

The product offer of the “group” is based on the perceived internal value of the product offer already under production at the involved companies; timber element prefabrication (Figure 1) and volume prefabrication (Figure 2). Hence, the main idea of the initiative is to use the timber volumes and timber elements where they are best suited. In conceptual design of the product offer it was identified that a large and difficult part of site-production is concerned with finishing off “wet areas” such as bathrooms and kitchens. Therefore it was decided to attempt to prefabricate such areas as volumes in order to better control the difficult finishing work on site. It was also decided to include as much as possible of the installations in the volumes since experience from volume prefabrication has shown that site production of installations is a common source of waste and higher quality can be maintained in factories.

The layout of the houses is based on volumes, but to achieve a higher degree of flexibility than can be accomplished with volumes alone, prefabricated timber elements are used to complement the volumes. Using elements, almost any kind of building can be produced. However, heavy efforts of standardizing the elements to simplify the manufacturing and site assembly processes has been made. This design effort has significantly reduced the number of different elements used. Effort has also been made from the involved companies to pinpoint and simplify the supply chain by reducing the number of suppliers for construction components, i.e., it has been decided on the suppliers able to deliver the required parts when needed and at the right price and quality.

Since this project has only undergone the conceptual design stage, it is not possible to report on perceived value for eventual clients or stakeholders. However what are interesting to note is why this endeavour has taken place and why the involved companies have such a high belief in the endeavour. The volume producer achieves a higher flexibility in his product offer, able to better meet new forms of client requirements while still offering a standardized product which is familiar and therefore possible to be produced efficiently. The element supplier, whose prefabricated element system is lacking in development and has only really been tested properly on one project, gains an increased share of the housing market and the possibility of developing its product offer in real applications. Even though it seems like this company endeavour has all possibilities of success on a fragmented construction market, it will be interesting to see if all ideas are transferable to practice. Based on experiences from a similar initiative, Bertelsen (2001) concludes that cost saving can be obtained if a long sequence of projects is established.
MANAGING THE VALUE STREAM THROUGH PREFABRICATION

PRODUCT OFFERS AND PREFABRICATION STRATEGIES

From the case studies, and the experience of the authors, a general material related value stream for a multi-storey timber housing project can be depicted as in Figure 3. This value stream can be used to relate the product offers presented in the three case studies. The prefabrication strategy in each case can be illustrated as a decoupling point (DP) between factory and on-site production, e.g., a decoupling point further to the right (downstream) would exemplify a prefabrication strategy utilizing more and more factory produced construction components (Björnfot and Stehn 2005).

![Figure 3: The case study product offers related as a decoupling point between factory and site production.](image)

The product offer of the first case company is aimed at producing construction components in the form of prefabricated elements. However, lack of time, or deficient knowledge of the construction process, lead to an undeveloped system for practical use which resulted in a two phase on-site construction process; assembly and structural finishing work (depicted as two decoupling points in Figure 3). The second case company’s aims at offering a complete volume system with limited adaptability to its customers (depicted as the decoupling point furthest downstream in Figure 3). Development of the volume system has lead to an increased control of factory and on-site variability through better control of the customer value generation process. The product offer in case study three concerns the integration of the element and volume prefabrication strategies aimed at an increased adaptability of the elements and an increased flexibility of the volumes so that new and before unattainable housing market segments can be reached. From the case study results it seems like the case companies utilize different prefabrication strategies to reach diverse segments of the housing market.

VALUE GENERATION FOR CLIENTS AND STAKEHOLDER

Each of the case companies have well defined product offers suited for market segments where customers have different perceptions of value and varying requirements on design involvement; Table 2 presents the main customers and product strategies of the three case companies. The element producer primarily offers its product to contractors who integrate the elements into their production systems. Since the element producer generally has no direct contact with the end customer, they primarily consider contractor requirements, e.g., high quality, low lead times and constructability. However, the integration of more
and more construction components (installations and finishing) within the elements seem to be an emerging demand from Swedish contractors, forcing the element company to move further downstream on the material value stream (Figure 3).

The customer base of case company two is fundamentally different from the element producer since they offer their product straight to the customer (often a landlord who represents tenants). The volume system therefore attracts a special type of customer who is provided with a well developed and tested product (they know what they get!) which is adaptable according to predetermined guidelines from the producer. The producer thus assure they can provide a system that can be produced efficiently and to a high quality (internal value), while the customer know they will be provided with the right product to the price and quality agreed upon (external value); unfortunately not a matter of fact situation in construction today emphasized by the development of value-adding decision making methods (see e.g., Thomson et al. 2004). The prefabrication strategy in case study three offers additional adaptability over the volume on the system level. Therefore, this system is not only suited to be offered straight to a landlord but also suited for a general contractor who wants to implement a well defined product into their production systems.

Table 2 The main customers and company product strategies for the case companies.

<table>
<thead>
<tr>
<th>CASE COMPANY</th>
<th>MAIN CUSTOMER</th>
<th>COMPANY PRODUCT STRATEGY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case Study 1 Element</td>
<td>Contractor</td>
<td>Strives towards being able to produce a complete element system targeted at contractors.</td>
</tr>
<tr>
<td>Case Study 2 Volume</td>
<td>Landlord</td>
<td>Strives towards keeping its volume system as straightforward as possible but also to increase the flexibility of the system and reach a larger market segment.</td>
</tr>
<tr>
<td>Case Study 3 Industrialized</td>
<td>Contractor, Landlord</td>
<td>Strives towards an increased flexibility in its product offer, aiming at an even larger customer base by an adaptable product offer to landlords and contractors.</td>
</tr>
</tbody>
</table>

Clearly, most customers want to be offered a product and then have the possibility of adapting the product to suit their own needs. This way of thinking is quite the opposite of today’s project oriented construction process where, commonly, a product is designed from scratch to suit the customers demands, instead of being offered to the customer as a well developed and tested product. In the studied case companies (especially case company two and three), the strategy of offering a product has lead to the companies being able to redirect resources from the customer requirements capture process to the continuous improvement of the value stream of their product offer. It seems difficult to implement such improvements for a project oriented construction process where customer value is defined and created, basically, from scratch, and where customers are often allowed to influence design decisions well into the production stage.

From the perspective of case company two and three, construction is not much different from the manufacturing industry, e.g., the automobile brand Volvo is marketed as the car of choice for families, while the BMW brand approaches a completely different
market segment, still defined but nonetheless customers with different perspectives of value. Manufacturing companies commonly offer a product that focuses on a specific market segment which allows for better control of customer requirements, but maybe most importantly; limiting the customers involvement in late design stages. Such a strategy frees additional resources to more tightly control the value stream and the associated supply chain (see e.g., Womack and Jones 2003). Why should value generation in construction be viewed differently?

DISCUSSION AND CONCLUSION

In this paper the product offer and the strategies for meeting customer demands has been studied for tree Swedish producers of prefabricated timber components for multi-storey housing construction; one producer of timber elements, one producer of timber volumes, and a fresh Swedish endeavour combining timber elements and volumes in an industrialized construction process. Albeit being a limited study in size and scope, the results are clear and indicate that the Swedish construction industry is slowly changing from the traditional project based generation of customer value to offering a specific product that the customer can adapt to suit his or her perspective of value. The results also indicate that a prefabrication strategy where a well defined and tested product is offered to customers has the additional effect of redistributing resources from the design process to the value stream and its associated supply chain. Such redistribution enables companies with a well developed prefabrication strategy to better control its value stream and to implement new and better ways of meeting customer demands while continuously improving their work and eliminating waste. This value generating process is in stark contrast to today’s construction process where value is built up from scratch and only realised, if at all, when the customer receives admission to the building.

The notion of precisely specifying value for the customer (the first principle of Lean Thinking) seems to have been partially forgotten in academic Lean Construction management research; more specifically the question of how construction should be structured to best generate value for the customer is rarely dealt with. This is surprising since Lean Thinking is about finding root causes to problems – value generation is an issue that so far remains unsolved in construction. From a critical perspective, the project organization so common in construction is merely a means to an end of producing a construction product. By means of offering a well developed and specified product, the one-of-a-kind nature of the construction product and the use of temporary organizations for its design and production are efficiently managed, instead value generation emerges as the main concern of companies. Lean Construction should therefore strive towards new forms of project organizations better suited to the product under consideration and better suited to the generation of value for all involved stakeholders. Prefabrication strategies’ offering specific products (albeit adaptable) to specific customers is such a Lean Construction strategy. Prefabrication in this fashion frees resource and opens the door for additional improvements within value streams (the second principle of Lean Thinking).
REFERENCES


Value delivery through ‘product offers’: a Lean leap in multi-storey housing construction

By: Anders Björnfot and Lars Stehn

(The paper has been edited to fit this thesis format, but the contents remain the same)

Value Delivery through ‘Product Offers’: A Lean Leap in Multi-Storey Timber Housing Construction
Anders Björnfot¹ and Lars Stehn²

Abstract
Among large Swedish contractors there is currently a specialization trend towards an increased use of prefabrication and complete systems in housing construction. The Lean Construction development up to date has focused on the management of value delivery for complex project based construction projects. Typical Swedish housing projects do not experience this broad complexity; instead the main challenge seems to be to better specify and deliver customer value. Currently, the Lean Construction methods available are of limited use for the generation of value in Swedish multi-storey housing construction. The aim of this paper is to examine the potential of the product offer (a well-defined and highly standardized building system developed from the value views of specific customers) as an aid in the generation and delivery of value for multi-storey housing construction. From the point of view of manufacturing and customer value, the product offer is considered a Lean strategy for integrated consideration of internal and external value. Case study experiences indicate that the product offer, through its stability and continuity, provides with Lean practices in marketing, design and manufacturing. Approaching Lean, small to medium sized Swedish producers should focus on improvements through Lean Manufacturing. However, since an emerging demand from the Swedish construction industry forces these producers to take a larger role in the construction process, more construction related Lean improvements must also be considered. In this regard, the product offer is demonstrated to be a promising Lean strategy for the Swedish housing industry.

Keywords: Lean thinking, Multi-storey timber housing construction, Value delivery.

Introduction
In Sweden, there are an increasing number of small to medium sized companies that have specialized in multi-storey housing construction by utilizing extensive prefabrication strategies (Björnfot and Sardén 2006). Among the large contractors, who mainly work in a traditional manner which involves large project organizations
and on-site work, a similar trend in specialization is observable. This specialization does mainly concern an increased use of prefabricated construction products as well as long-term stable client relations. Drivers for this specialization trend are a demand for reduced construction costs but also a pure business perspective where the higher profitability experienced by specialized companies is sought (10% compared to about 2% profitability for the large contractors).

The amount of pure waste in traditional construction projects is striking; a Swedish study reports that only about 20% of performed work is directly value adding (Josephson and Saukkoriipi 2005). Lean Construction takes on this challenge by striving to better meet customer demands and to dramatically improve the construction process as well as its product (Howell 1999). Lean has proved to be a valuable philosophy for construction; Ballard and Howell (2004) and Emmitt et al (2005) report on successful implementations. However, positive experiences are mainly related to the application of Lean practices on complex project oriented construction projects through the use of methods such as the Last Planner System (Ballard and Howell 2003). Typical Swedish housing projects do not experience this broad complexity; instead one of the main concerns seems to be a lack of knowledge of the customer value generation process (Olofsson et al 2004, Björnfot and Sardén 2006, Höök 2006).

Based on empirical results from three Swedish multi-storey timber housing producers, Björnfot and Sardén (2006) identified the application of product based technical platforms, called ‘product offers’, as means for the producers to create stable production systems and supply chains for efficient management of customer value and improved profitability. For these producers, the product offer represents a strategic change where the organization is gradually becoming more Lean and ready for an implementation of specific Lean practices (Green and May 2005). As such, a strategic change through ‘product offers’ ties in well with the principles of Lean Thinking (Womack and Jones, 2003), i.e., the key is to specify customer value by specific products and then to never lose sight of this value as the value stream is reformed and none-value adding activities are removed.

The aim of this paper is to evaluate the potential of the product offer as a means of facilitating the delivery of value in housing construction. First, Swedish housing construction is described after which value delivery through Lean Construction is discussed and analysed. Through the principles of Lean Thinking and experiences from the Swedish housing industry, the product offer is then argued for as a strategic application of Lean which aids in the generation of internal (own) value and the delivery of external (customer) value. Finally, empirical results from a fresh Swedish development initiative in multi-storey housing construction are presented to provide a deeper understanding of how a product offer is developed and how the product offer can act as a Lean driver for value delivery and value generation.
The nature of value in housing construction

The Swedish housing industry

The large majority of Swedish producers of detached housing have well developed production systems where the product (the house) is prefabricated and targeted at specific customers who enjoy great flexibility within the constraints of the production system, e.g., restricted architectural and floor-plan options. As an example, the largest Swedish producer of detached housing offers limited flexibility but offer a fixed set of options (much like a car manufacturer) giving their customers (private home owners) a feeling of flexibility at a very competitive price. In the detached housing market, there are also producers who offer customers greater flexibility -- their prices are generally higher due to a more complex product and production system. The detached housing producers have realized that specialization is a condition for profitability and ultimately survival and that it is very difficult to be profitable by approaching the requirements of every possible customer. As such, these producers pursue of value delivery for specific customers is similar to companies within the manufacturing industry.

Even considering the long-term success of the detached housing producers, the Swedish multi-storey housing industry has been slow to adapt; the industry is still in an era of traditional production where construction companies generally compete for their customers with production systems suitable for a large variety of customers. As a consequence, the construction process is prone to waste generation for both customers and construction process participants (Björnfort and Sardén 2006). Furthermore, Josephson and Saukkoriipi (2005) argued that construction companies trying to be best at everything by pursuing every possible project create further waste since much resource is spent without any result in extensive and frequently unsuccessful bidding competitions.

In the multi-storey housing market, there are a number of small- to mid-sized producers who have realized that it is possible to gain benefits from specialization. A key aspect of this specialization is a clear identification of the customer and the development of a technical platform, a product offer (similar to detached housing), which is based on the values of the targeted customers. As such, the product offer is a well-defined and highly standardized building system (the ‘complete package’ including design, manufacturing, assembly and supporting services such as long-term quality assurance, financial aid, etc.) which allows for the design of a stable and efficient long-term production system and firm control of the supply chain. To understand the product offer as an alternative Lean strategy for value delivery in multi-storey housing construction, we start by describing value management through Lean Construction.

The value concept

In traditional housing construction projects it is common to initiate the design process using a vague conceptualization of the end structure which leads to an
inefficient design process where extensive customer involvement only increases complexity (Bertelsen and Emmitt 2005) - the design changes as the perception of value for the client changes. An additional effect of the fragmented construction process is waste during the production phase which in Swedish housing accounts for up to 35% of the production costs (Josephson and Saukkoriipi 2005) and adverse participant relations (Sardén 2005) leading to even more waste in a business perspective as prices are continuously negotiated. It seems that a lack of consideration for the value generation process can have dire consequences for all project stakeholders.

Value, as defined in Lean Thinking (Womack and Jones 2003), refers to materials, parts or products - something materialistic which is possible to understand and to specify (Koskela 2004). Construction is a process of delivering this value to the client through a temporary production system (Bertelsen and Emmitt 2005). The client is often an organization representing owners, users and society who values different things at different times during the life of the building, e.g., durability, usefulness, beauty, flexibility, environmental aspects, etc. (Bertelsen & Emmitt 2005). The other construction team members also have values to fulfil, but their main concern should be to deliver the best possible value to the client whom otherwise would look elsewhere (Emmitt et al 2005).

Value may be divided into external and internal value (Emmitt et al 2005) - external value is the clients’ value and the value which the project should end up with, while internal value is the value that is generated by and between the participants of the project delivery team (contractor, architects, designers etc.). In this paper internal value is synonymous with profitability and independence (Cuperus and Napolitano 2005). Independence provides stakeholders with increased control over the internal value generation process through the shielding of their production systems from external sources of variety (such as late unforeseen design changes).

Even though the project delivery team tries very hard to design and offer a product to suit the specific wishes of the customer, the result of the value generation process is often a building different from the initial customer conceptualization, especially so after municipal and governmental restrictions has been considered. It seems that the way value is currently generated in construction projects leads to increased complexity and commonly results in waste generation at the expense of providing value for stakeholders. As a result, project stakeholders inevitably end up salvaging as much as they can out of construction projects through claims (Sardén 2005).

**Value delivery through Lean Construction**

One aim of Lean Construction is to aid in the delivery of external value by the management of the internal value generation process. To aid in internal value generation, the most commonly referred to Lean techniques in construction are work flow control through the Last Planner system (Ballard and Howell 2003), value stream mapping (Rother and Shook 2001, Arbulu and Tommelein 2002), just-in-time
production and supply-chain management (Low and Mok 1999) and pokayoke or the five why’s technique (Tsao et al 2005). Other interesting and increasingly popular development efforts aiding in the delivery of external value are improved planning tools such as Line-of-Balance (Kenley 2005) and computer aided design using 4D CAD (Rischmoller et al 2006). Through Lean Design principles (see e.g. Freire and Alarcón 2002) late design changes becomes possible. However, if changes are made too late in the process they may generate waste in stable production systems (Stehn and Bergström 2002).

In Lean Construction, the project is considered a fundamental feature of construction and the production system is designed with the project as its core. In traditional construction projects, external value is generated in the design phase through negotiations. Even if there are no Lean Construction methods available to specify external value there are accepted methods which aid in the value generation process; examples of such methods are partnering and concurrent engineering (Cheng and Li 2004) with incentives for team work in design and the facilitation of value generation throughout the iterative design process. Computer aided design is slowly gaining acceptance as an aid in external value generation (Rischmoller et al 2006). Another interesting development effort for construction is target costing which aims to decrease costs so that a required profit level can be assured (Granja et al 2005), i.e. an integrated internal/external value view.

Based on experiences from the implementation of Lean Production in the UK auto industry, Oliver et al (1996) conclude that Lean principles are effective at fine tuning a system which is already basically under control, but the principles are not by themselves capable of bringing order to chaos. Construction is more or less stable since the structure of construction (e.g. participants, production methods, tools, etc.) has not undergone any fundamental changes for the past century. However, within organizations and in the execution of work there is still a large variety originating from poor process control and unforeseen and uncontrollable external factors such as weather and traffic. Swedish prefabrication initiatives are structurally changing the multi-storey housing industry towards a kind of manufacturing; one of the main Lean Construction strategies (Bertelsen 2004). A fundamental part of this change is the product offer which aids producers in the delivery of external value by stabilizing their internal value generation processes.

**Value delivery through product offers**

The product offer approaches Lean Construction on a strategic level; it seems to be a new way of thinking in the delivery of value for the multi-storey housing industry, rather than an implementation of specific Lean practices. The principles of Lean Thinking (Value, Value stream, Flow, Pull and Perfection) advise producers on how their production systems should be transformed so that value can be maximized and waste minimized (Womack and Jones 2003). In terms of Lean thinking, production should be aimed at satisfying customer value by specific products (external value), while value for project participants (internal value) should come from waste reduction activities and continuous improvements within
the value streams through the promotion of activities enabling Flow, Pull and Perfection.

Koskela (2004) argues that the Lean Thinking principles are insufficient for the task of changing construction to Lean. However, the principles promote important features which can facilitate a general change of perception of production in multi-storey housing construction, particularly of how value is delivered and improved upon. In Lean thinking customer value (delivered as a product and/or service) is clearly of primary concern and governs the transformation of the production process so that value can be delivered as efficiently as possible. Consequently, delivering customer value means organising around a product and/or service which provides continuity and stability (Garnett et al 1998).

**The product offer: an application of Lean principles?**

The *product offer* takes on the challenge of controlling the variety inherent in construction through continuity and stability. Understanding the *product offer* through the Lean Thinking principles promotes the *product offer* as a strategic application of Lean for value delivery in multi-storey housing construction. Lean characteristics (as viewed from Swedish housing industry practice) introduced into the production system by the *product offer* are outlined in Table 1. The *product offer* is specified and detailed from customer requirements (*Value*). Managing customer value through the *product offer* forces the customer to lock their options to a specific technical platform (building system) offered by the producer. Locking customer options allows the producers to be in control of a stable value generation process where customers are allowed flexibility through selected add-ons and options such as façades, apartment layouts and interior finishing. Consequently, value is specified by specific product for specific customers, which enables stability.

In production system design, the stability of the *product offer* is discerned through the specification of activities and resources required for product realization (*Value stream*). Continuity provides a steady foundation (process stability) for continual improvement through identification and elimination of non-value adding activities (*Flow*) (Table 1). The *product offer* provides a foundation for successful supply chain management which is facilitated by lower variety in delivery (quality, time and amount) and continuity for suppliers who are provided with a stable base from which to facilitate their own profitability through improvement programs (*Perfection*). In a sense, a transparent production system where everyone can see everything and everyone is working towards the same goal is facilitated by and a requirement for, a *product offer* since stability and continuity cannot be reached without a stable supply chain (Table 1).

If customization is of value to the customer, which is often the case, then the *product offer* must ensure enough flexibility so that value can be delivered (*Pull*). According to Naim and Barlow (2003), profitable customization requires a robust supply chain for changes in both product volume and product variety. Ensuring enough flexibility is a continuous struggle for housing producers relying on
extensive prefabrication strategies (Stehn and Bergström 2002) since the customers’ perception of value does change over time. Hence, the product offer must continuously develop so it can be adapted to the changing market (Table 1).

Table 1: Lean characteristics introduced by the product offer.

<table>
<thead>
<tr>
<th>Lean principle</th>
<th>The product offer implies...</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>...detailed product specifications developed from customer requirements captured on the market where the product is intended.</td>
</tr>
<tr>
<td>Value stream</td>
<td>...definition of the specific resources and activities required for supply chain management and product realization.</td>
</tr>
<tr>
<td>Flow</td>
<td>...control of a stable value stream so that value adding activities can be better managed and so that waste can be eliminated or reduced.</td>
</tr>
<tr>
<td>Pull</td>
<td>...flexibility and adaptability to current and future customer demands and the ability to find ways of reducing lead times.</td>
</tr>
<tr>
<td>Perfection</td>
<td>...stable and transparent processes and operations allowing for continuous improvements by experience feedback.</td>
</tr>
</tbody>
</table>

To conclude, the product offer provides Lean characteristics throughout the production system; its stability creates a stable value stream which results in a stable production system with activities which can be continuously improved upon so that flow can be established and internal value updated.

Application of product offers in Swedish multi-storey construction

Currently there are only a few signs of any conscious or pronounced implementation of Lean in Swedish multi-storey housing construction. Increasingly Swedish producers are adopting the product offer strategy to improve profitability. Two examples of product offers for multi-storey housing construction are here reviewed (Table 2) in relation to the characteristics introduced by the product offer (Table 1).

The first case describes the product offer of a Swedish producer of prefabricated structural timber wall and floor elements (E) (see Björnfot and Stehn 2005, Sardén 2005, Björnfot and Sardén 2006). The prefabricated elements provide a complete structural system (including the load-carrying system, installations and even finishing) which are assembled on the construction site by a general contractor.

The second case describes the product offer of a Swedish producer of Timber volumes (V) (volumetric pre-assemblies featuring ready-to-use living space) (see Olofsson et al 2004, Björnfot and Sardén 2006, Höök 2006). The volumes are fully prefabricated with interior and exterior finishing before being shipped to the construction site and assembled by the producer.

As a result of their product offer, Lean characteristics can be observed throughout the timber volume producers (V) production system (Table 2). Examples include:
- a stable and continuous value stream and supply chain,
- a well developed manufacturing and site assembly process,
- customer pull through flexibility and adaptability and
- a shared process design with suppliers and academics to facilitate continuous improvements.

Table 2: Analysis of introduced Lean characteristics by two Swedish product offers.

<table>
<thead>
<tr>
<th>Lean principle</th>
<th>Perceived Lean characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Value</strong></td>
<td></td>
</tr>
<tr>
<td>Element (Flat Panel)</td>
<td>Volume</td>
</tr>
<tr>
<td>E manufactures elements for contractors who integrate them into their production systems. The elements are relatively untested in practice.</td>
<td>V manufactures and assembles prefabricated volumes offered straight to the customer, often through long-term contracts with landlords.</td>
</tr>
<tr>
<td><strong>Value stream</strong></td>
<td></td>
</tr>
<tr>
<td>E is a known producer of glulam on which its element manufacturing process is based. Increased integration of installations has forced the supplier to bring specialized subcontractors in-house for assembly.</td>
<td>V controls the whole value stream which consists of long-term relations with subcontractors who are brought in-house, with assembly teams for on-site construction and with suppliers for a stable supply chain.</td>
</tr>
<tr>
<td><strong>Flow</strong></td>
<td></td>
</tr>
<tr>
<td>E is primarily a manufacturer with no previous experience in the construction process resulting in initial waste due to rework and delays.</td>
<td>V has a well developed, stable and continuous value stream which is continuously reviewed so that work can be improved upon.</td>
</tr>
<tr>
<td><strong>Pull</strong></td>
<td></td>
</tr>
<tr>
<td>E develops its elements for each particular project. An emergent demand from contractors is to increase the degree of prefabrication and to provide with supporting services, such as assembly.</td>
<td>V offers a well known, high quality product with predefined characteristics. Client involvement is mainly limited to interior and façade design which allows for shorter lead times.</td>
</tr>
<tr>
<td><strong>Perfection</strong></td>
<td></td>
</tr>
<tr>
<td>E is affected by the variety of the construction process which results in waste during manufacturing and delivery. They strive to become more independent and also offer a service in support of their product.</td>
<td>V is continuously striving towards capturing more and new market shares. The stable value stream enables them to utilize transparency and to generate improvement programs.</td>
</tr>
</tbody>
</table>
Volume producers are still far from being Lean since no Lean practices can be discerned in their current work. But it seems that the stability incurred by the product offer presents a good opportunity to implement Lean practices, such as visual control and work smoothing.

At the timber element producer (E) there are not many signs of Lean practices (Table 2). It is clear that the element system is not as well developed as the volume system. However, the element producer’s ambition is independence from the variety of the construction process, similar to the development effort by the volume producer.

The experiences of these two product offers (Table 2) provides insight into the fundamentals of developing a successful product offer strategy. Successful product offer development requires clear specification of the product and associated services (product specification) related to customer requirements so that the value asked for is what is produced and delivered. Close relations with current and future customers (external relations) are important so that the product offered can be adapted to changes in what customers want. To facilitate work in a changing market, stability within the production system is required (internal relations) as well as control over the delivery from external suppliers (Supply chain management). In the next section, a Swedish initiative at product offer development is reported on where the mentioned aspects are reviewed.

A Swedish product offer development initiative

The initiative reported on involves three Swedish timber component producers and one firm of architects. The two producers described in Table 2 are part of this initiative. The aim is to increase the producers’ share of the multi-storey housing market. As of now, the product offer has not been seen in practice, yet a discussion of how the product offer has been developed is of interest to deepen the understanding of its application as a Lean strategy for housing construction. The presented results are based on data collected over a one year period including interviews with managers and production personnel, participation at design meetings and documentation relating to the initiative.

Product offer development & specification

The competitive edge of the developed product was stated as offering a “complete package” (from design to assembly) in a cost and time efficient industrialized construction process involving the main products of the companies involved; prefabricated timber elements and volumes (Figure 1). The companies all have high expectations of the outcome of the initiative; the volume producer achieves improved flexibility of his product offer enabling consideration of new client values while still producing a familiar product. The element producer, whose prefabricated element system is lacking in development, would gain an increased share of the housing market and the possibility of developing their element system in real applications. As the architectural values of customers change, the long-term involvement of the architect ensures that new architectural forms and layouts
can be developed that specifically support the *product offer* without compromising the manufacturing processes.

![Diagram showing volumes and elements integrated into a product offer](image)

**Figure 1:** The *product offer* integrating prefabricated timber volumes and elements.

The main customer for the *product offer* was identified as landlords who offer flats to tenants at a price of around 110 €/m² (living area) in multiple floors. The calculated total cost for a regular sized apartment was 1300 €/m² (compared to about 1700 €/m² per apartment in traditional housing construction). Based on these costs a target *production cost* of 800 €/m² was agreed for the development of the *product offer*. The layout of the houses is based on volumes. To achieve a higher degree of layout flexibility than can be accomplished with volumes alone prefabricated timber elements are used to complement the volumes. The main idea was to use both volumes and elements where they are best suited. A large and difficult part of on-site production is finishing off “wet areas” such as bathrooms and kitchens. It was decided to attempt to prefabricate such areas as volumes and to include as much as possible of the installations since experience has shown that site production of installations is a common source of waste and that higher quality can be maintained inside factories.

During design development elements, such as wall and floor elements, were standardized to simplify the manufacturing and site assembly processes. This design effort significantly reduced the number of elements used. Standardization was considered an important aspect in the promotion of a construction process where standard work in manufacturing, delivery and site assembly could be utilized. Surprisingly, it was not until late in the process that standardization became a key aspect. By the end of the development process, a production cost of 900 €/m² was achieved which was higher than the targeted cost. However, the delivery team is continuously looking for improvements so that the target cost can be achieved.

**Relations & supply chain management**

Through the *product offer*, the producers are able to use a simplified tendering process similar to the practice already used by the volume supplier (Olofsson *et al* 2004). The simplified tendering process involves relational contracting among the
producers so that the customer does business with one delivery team instead of a multitude of independent subcontractors. The main customers for the product offer are landlords but the improved flexibility makes the product offer attractive to contractors as well. The increased flexibility of the product offer also enables clients to become further involved in the design process without compromising the stability and continuity of the producers manufacturing processes.

The standardization effort has also resulted in reduced production costs due to cost and time savings in manufacturing and assembly. This allowed the delivery team to pinpoint key component suppliers and to simplify the supply chain by reducing the number of suppliers, i.e. it was decided on the suppliers who would be able to deliver required components when needed and at the right price and quality. The delivery team has a desire to integrate lower tier component suppliers into their value chains and to engage in long-term relations with suppliers so that stable supply chains can be formed. The aim of this effort is to

- allow the delivery team to be in control of the whole supply chain and
- involve everyone in continuously improving the product and associated processes together.

A goal was to develop an on-site assembly process with manufacturing characteristics, i.e. use of automation for material handling and movement. Additionally, a dry site production process was aimed at through the use of a covering tent. Through this effort, the construction site becomes much like a factory in which components are shipped in and assembled as they are delivered. Such an assembly process demands attention on logistics for Just-in-Time delivery of components. To facilitate cooperation within the delivery team and control of the production system, a computer support system is being developed. The aim of the computer system is to

- allow for simultaneous sharing of information between the involved producers to aid in the design process,
- facilitate short lead times with increased customer involvement,
- support the manufacturing processes and
- guide the delivery of components to manufacturing and to the construction site.

**Concluding case study remarks**

Deciding on a course of action, in this case the combination of elements and volumes provides with stability and continuity - the variety of construction is integrated into the product offer which provides with a stable foundation for client negotiations, design development, production system design and continuous improvements of both the product and associated processes. Most of the development efforts in support of the product offer either enables Lean practices or are influenced by them, i.e.

the product is highly standardized to facilitate standard work in manufacturing and assembly,
internal relations are managed through target costing and relational contracting, external relations are managed through flexibility and the supply chain is managed through long term supplier relations to enable continuous improvements.

Multiple similar endeavours to this case are currently being developed in Sweden characterised by a stable product offer acting as a driving force for improvements - it seems as if the product offer strategy provides an initial stimulus towards Lean Thinking in multi-storey housing construction.

Discussion

The aim of this paper was to evaluate the potential of the product offer (a well-defined and highly standardized building system developed from the value views of specific customers) as a strategic application of Lean to facilitate the delivery of value in multi-storey housing construction. It was argued that the product offer approaches Lean Construction on a strategic level; it is a new way of thinking about the delivery of value for the multi-storey housing industry, rather than an implementation of specific Lean practices. Based on the principles of Lean Thinking it was argued that the application of the product offer is a Lean strategy for management of value delivery and value generation. Case study experiences indicate that the product offer, through its stability and continuity, provides with Lean practices in marketing, design and manufacturing.

Developing a product offer requires input from many specialized subcontractors who are often acting independently - they must work together towards a common goal instead of “minding their own business”. The product offer development initiative described in this paper is an example of teamwork over organizational borders through relational contracting. Relational contracting provides stakeholders with incentives to make their best effort for the project, to use innovative thinking and to continuously improve on their own work (Matthews and Howell 2005). The case study experiences showed that it is possible to work together and deliver value in new ways by breaking the restraining influence of the traditional project oriented construction process.

The view on value differs between industries and even cultures. Therefore, the application of Lean will be different. A contractor of complex industrial projects may for example want improved control of site production through Last Planner while a producer may want manufacturing process improvements through practices such as the Toyota Way (Liker 2003). The similarity of these efforts is a new way of thinking, Lean thinking. Approaching Lean, small to medium sized Swedish suppliers should primarily focus on improvements through Lean Manufacturing. However, an emerging demand from Swedish contractors forces these suppliers to take larger responsibility in the construction process. In this regard, the product offer is a Lean strategy for Swedish producers which, if fully developed and correctly applied, enable them to satisfy external value while being able to pursue profitability through stable production systems and supply chains.
References


Appendix A  Interview questions with site workers

Appendix B  Description of the multi-storey housing production process
Appendix A  Interview questions with site workers

Appendix A presents the interview questions which were discussed with the site workers.

The areas of interest discussed with the site workers during the interview session (Chapter 3.4) are presented below. When deemed necessary, additional questions were formed to more in detail pinpoint problems and solutions within each area.

- How has the offloading of the elements worked as intended? What problems have been identified and how can the offloading be improved?
- Has the construction site been freely passable during assembly? What can be done to improve the passage on the construction site during assembly?
- Has the elements been assembled straight from the trucks or has some kind of storage been used? How can assembly be improved to minimize storage?
- How has the weather protection system (the tent) been handled? Does the protection serve its function and how can its handling be improved?
- How has the work with the wall linings progressed? What has been the implication for wall element assembly and what can be improved?
- Has the connection between the elements (wall to wall, floor to wall, and floor to floor) worked as intended? Are there any tolerances issue? Are there any issues with installation connections?
- Has the assembly process been improved from house 1 to house 2 and house 3? What specific detailing and work practices has been developed to facilitate the assembly process? Has any problems been solved as production has progressed? Are there any issues that remain unsolved?
- What kind of finishing work is required to finish the wall and floor elements? What are the identified problems in finishing work and how can they be solved?
- How has the material required for finishing work been stored and how has this material been delivered to the work spaces? Has storage been required, if so how and where has the material been stored? Would it be possible to reduce or completely eliminate the need for storage?
- How is the work environment in finishing work? Is it possible to ease the strain of finishing work, if so how? What products could be prefabricated to further facilitate finishing work?
- Have there been any tolerance issues with installation or finishing work in general? How would it be possible to improve on work so these issues are eliminated?
Appendix B  The multi-storey housing production process

First the activities performed are presented after which the assembly process and finishing work are illustrated.

B.1 Activities during assembly and finishing work

The activities during assembly were presented in Table 4.1. Table B.1 presents the activities during structural and interior finishing; the activities were obtained from site observation and the original Gantt schedule for the project. These activities were in Paper III, Figure 6 presented in a Line of Balance schedule where the on-site observed assembly sequence (Figure B.1) was used to further detail the presented schedule.

Table B.1  The structural and interior finishing activities observed during site production.

<table>
<thead>
<tr>
<th>STRUCTURAL FINISHING ACTIVITIES</th>
<th>INTERIOR FINISHING ACTIVITIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>‘Adjust Ceiling’</td>
<td>‘Painting’</td>
</tr>
<tr>
<td>‘Finish Ceiling’</td>
<td>‘Tiles kitchen’</td>
</tr>
<tr>
<td>‘Sprinklers piping’</td>
<td>‘Electricity finishing’</td>
</tr>
<tr>
<td>‘HVAC installation’</td>
<td>‘HVAC finishing’</td>
</tr>
<tr>
<td>‘Electricity installation’</td>
<td>‘Finishing bathroom’</td>
</tr>
<tr>
<td>‘Apply gypsum on bearing structure’</td>
<td>‘Plasterboard walls’</td>
</tr>
<tr>
<td>‘Floor elements finishing’</td>
<td>‘Flooring (wooden) panels’</td>
</tr>
</tbody>
</table>

Figure B.1  Illustration of the assembly order for ‘outer wall’ and ‘floor elements’. Refer to Table 4.1 for an overview of the activities and their duration.
B.2 Illustrations from the assembly process

Figure B.2 illustrates the use of the weather protection system during on-site assembly. As the timber elements were made ready for assembly, automation was used to move the tent so that the elements could be assembled. The covering tent was considered a success since it enabled a dry production process, i.e. assembly could be performed in any weather. The use of the covering tent was especially useful during rain (and poor weather in general) where a gap was briefly opened to allow the element to be brought in, and then the gap was quickly closed while the elements were fastened.

Figure B.3 illustrates the site logistics during assembly, i.e. how the elements were delivered to the construction site (truck and trailer) and staging areas used to store elements before assembly. As can be seen on the pictures, the staging areas caused temporary disruptions in the flow of work on the construction site since the only passable road through the construction site was blocked.

Figure B.4 and Figure B.5 illustrates the assembly process for the floor and wall elements respectively. First the elements were delivered to the construction site and then the elements were off-loaded before being hoisted into place using a tower crane. For assembly, two workers and a tower crane was used to connect the element and then two workers were used to fasten the elements in their proper place in the building. Especially note how the covering tent was moved to allow for assembly to be performed.

Figure B.2 The weather protection system (observed through a web-camera).
Figure B.3  Site logistics (observed through a web-camera).

Figure B.4  Assembly of floor elements (observed through a web-camera).
Figure B.5  Assembly of wall element (observed through a web-camera).

B.3  Illustrations from finishing work

Figure B.6 illustrates some of the many different types of connectors required for assembly and finishing work – wall to wall connections, floor to wall connections and sub-ceiling to wall connection. Structural finishing was overall considered problematic due to the many connectors used and from the pictures it can be seen that structural finishing also was complicated due to lack of space resulting in many complaints of poor work conditions.

Figure B.7 illustrates some of the typical activities performed in structural finishing – in the case study results (Chapter 4.1) it was described that the sub-ceiling was not finished when it was delivered to the construction site. Typical activities that were needed to finish the sub-ceiling are shown in the figure – sprinkler installations and adding gypsum boards to the sub-ceiling (especially notice the poor working conditions of working bottom-up). Another common problem associated to traditional construction is bad order on the construction site (bottom-right picture). There were numerous complaints from workers and management relating to bad order during production.
Figure B.6  Connections used in assembly (observed through site visits).

Figure B.7  Structural finishing work (observed through site visits).
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