Modularity in Industrialised Timber Housing

A Lean Approach to Develop Building Service Systems

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Luleå University of Technology 2009
MODULARITY IN INDUSTRIALISED TIMBER HOUSING

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“In my end is my beginning”
(Mary, Queen of Scots)
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Luleå, November 2009.
Abstract

Modularity has been applied in various disciplines, e.g. manufacturing, computer, cognitive science and education. General advantages are platform thinking and module variants which provide a range of product variants using a small number of components. However, the field has not been fully explored within construction.

Sweden has taken a leading role within industrialised timber housing. Much effort has been put in research and development of the timber structural system. Thereby, the building service systems (electrical and HVAC systems) has fallen behind in development. Currently, there are several actors involved, (e.g. consultants, subcontractors, wholesalers) that are individually procured on short-term agreements. The actors remain in the traditional culture with dispersed views on value. To be able to break this dependency, enhanced industrialised practice for the building services is sought. Modularity is argued to aid in reducing the variation in production, lowering lead times and achieving control of material supply. Through modularity, production control can be achieved and value can be better managed, issues which are prevailing in industrialised timber housing.

The purpose of the research is to evaluate the feasibility of modularity for building service systems within industrialised housing in Sweden. The thesis is based on two appended papers, discussing how modularity can be applied to industrialised housing, considering value generation and production control. The research strategy has been to follow previous case conclusions in the design of the next case. Empirical data have been gathered from five case studies ranging from a market survey to a consultant procurement. Five industrial housing companies have participated and data have also been collected from consultants and subcontractors.

The results show that influence from traditional culture is particularly evident for the building service systems, as much work is still located on-site and actors in the supply chains act individually to optimize their own values, leading to lack of production control through e.g. faulty drawings. Further, the importance of cooperation within the trade is underlined in order to shield from the protectionism in the building service trade. The implication is the development of industry-wide common modules capturing internal values, and a company driven development process for management of company specific external values.

The data have been analyzed with a generic set of module drivers and the relation to value and production control, to identify forces for modular division. The findings point out the importance of drawing validation, possibility to isolate the process for parallel assembly and purchasing control through reduction of articles.

The general conclusion is to design base module components only comprising necessary systems, which can be adapted to a generic building system. The suggestion is the development of a building service shaft and a building service inner ceiling. The analysis results emphasize the importance of interface design. In this sense are also included interfaces within the process and the supply chain, i.e. between activities and actors in the production process.

Abstract
SAMMANFATTNING

Modularisering har tillämpats inom olika ämnesområden, t.ex. tillverkningsindustrin, datorbranschen, kognitiv vetenskap och utbildning. Generella fördelar är ett plattformstänkande och modulvarianter som ger en rad olika produktvarianter genom få antal komponenter. Däremot har modularisering inte blivit utforskat i samma utsträckning inom byggbranschen.

Sverige har en ledande roll inom industriellt byggande av bostäder i trä. Mycket forskning och utveckling har inriktats mot stornsystemet medan installationsystemet (el och VVS) har fått mindre uppmärksamhet. Installationssystem (el och VVS) hamnar ofta för sent i utvecklingen. Inom installationsbranschen finns flertalet aktörer (t.ex. konsulter, underleverantörer och grossister) som upphandlas individuellt, på korta avtal. Dessa befinner sig fortfarande i den traditionella byggkulturen med individuellt värdeskapande. För att kunna bryta denna kultur, söks en utveckling av det industriellt byggande. Modularisering bidrar till minskad variation i produktion, minskade ledtider och bättre styrning av materialesupplyering. Genom modularitet, kan produktion och värdeskapande tillgodose sig, något som efterfrågas i dagens industriella byggande.


Resultatet av den traditionella byggkulturen är särskilt starkt för installationsbranschen då mycket arbete fortfarande utförs på byggarbeteplassen och aktörer i försörjningskedjan agerar individuellt för att optimera sina egna värden. Detta leder till brist på produktion och kontroll genom att samarbeta slippas ut av systemet. Detta resulterar i brist på produktion och kontroll genom att göra det svårare att göra en korrekt val av system och komponenter. Utvecklingen av nya system och komponenter är därmed mycket viktig för att kunna tillämpa modularitet på ett effektivt sätt.

Resultaten av empiriska data har analyserats med generella moduldrivare relaterade till värde och produktion och kontroll för att identifiera möjligheter till uppdelning i moduler. Resultaten betonar vikt och möjlighet för parallel montering och kontroll på inköp genom minskning av antalet artiklar. Detta innebär att problemen kan lösta enbart genom att använda moduler som enbart omfattar nödvändiga system och som kan anpassas till ett specifikt byggprojekt. Detta leder till att förstå de olika aktörers roll och hur de kan arbeta tillsammans för att uppnå ett bättre resultat.


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APPENDED PAPERS

Paper I:

Paper II:

APPENDICES

Appendix 1: Consultant Procurement Questionnaire
Appendix 2: Production process activities for electricity
Appendix 3: Assembly time for electricity in two volumetric units
1 INTRODUCTION

The chapter introduces the reader to the research field. This is followed by the aim and purpose of the thesis.

1.1 Background
Modularity is a concept which is far from new; the basic idea to combine blocks to attain variety has probably been practised since ancient history (Blackenfelt 2001). Further the concept has been in use for a long time within a more modern industrial context. For example, Ford's T-model included common and variety elements and Scania was thinking in this sense already during the 1940s (Hultdin et al. 1996) for whom the modularity concept has played a key role since the early 1980s. General advantages from modularity are platform thinking and module variants that will provide a range of product variants using a small number of components.

Modularity has been applied in various disciplines, such as manufacturing, computer, cognitive science and education. However, the field has not been fully explored within the realm of construction. The use of production platforms and modularity has been studied in housing projects in order to gain control over the massive amount of components that define a house (Veenstra et al. 2007). The construction housing branch, where the aim is to have high levels of prefabrication, i.e. industrialised housing, has seen some efforts to investigate modularity (e.g. Björnfot and Stehn 2004; Martner et al. 2008). However, there are still issues to be solved and the method has to be further investigated.

Industrialised timber housing is a branch of the construction trade in Sweden, which has increased its share on the market. Sweden is expected to take leading in the field of wood and timber (DS 2004). A governmental ordered investigation Skärpning Gubbar! (SOU 2002) pointed out that the Swedish construction industry has to change in order to be able to gain control over the costs, i.e. defects and production efficiency. One way to manage these problems is to apply an industrial practice to construction (Beverket 2006). This strategy aims for increased degrees of prefabrication in closed production facilities with high levels of added value and large transportation distances.

In its development the timber industry has accomplished to validate timber as a sustainable material in the construction society. The initial step was a confirmation of working solutions where timber proved to fulfil functional demands. Techniques for process and construction were developed, in the next phase utilising timber's unique combination of strength and low weight, for increased improved prefabrication.

The third ongoing step implicates the final adaptation into the end product—the building. This means that building service systems (Electrical and HVAC systems) have to be integrated with the structural system, which has to be conducted under the terms of industrial practice.
A problem for development is how the building service systems are subordinated to the structural system in its design (see Figure 1a), derived from the absence of a systems view on the building service systems.

a) Structural system is superior

![Diagram a)](image)

b) Building is superior

![Diagram b)](image)

Figure 1. Interrelations between systems within housing; a) Current state, with superior structural system; b) Desired state, building is superior and value in focus.

The building service systems depend on the prevailing structural system, which then defines the building. Consequently, there will be problems with value capturing. Emmitt et al. (2005) emphasise the importance of taking on a holistic view already early in the process in order to get everything right from the beginning. For example, the current view on the building will experience problems to manage alterations in customer demands and revised regulatory framework. The desired state is displayed in Figure 1b where the service systems along with the structural system are individually optimised. This means that the service systems can be better managed in accordance with customer demands and governmental regulations.

The conclusions from Höök (2008) include the problem of a prevailing traditional culture within industrialised housing, resulting in a lack of standardised work methods, loyalty problems within the workforce and absence of management commitment. Apleberger et al. (2007) state that development of industrialised housing should be built on long-term relations on both ends of the supply chain, i.e. customers and suppliers. Brege et al. (2004) highlights the problem of fragmentation in the relations between buyers and suppliers and the threat of weak management leading to ineffective organisations. A consequential problem with fragmented links within the industrialised housing trade is the lack of production control. This is a key issue to address for industrialised builders as disruptions in production will lead to errors in the overall process.

MODULARITY IN INDUSTRIALISED TIMBER HOUSING
1.2 Motive for modularity

In its simplest form a module refers to a building block with designed interfaces. The complete set of modules, the platform, forms a common structure from which a stream of derivative products can be developed, marketed and produced (Ericsson and Erixon 1999 pp xi).

When scientifically investigating modularity, it is concluded that much research has been conducted within manufacturing and computers (see e.g. Morris and Donnelly 2006; Baldwin and Clark 1997), but within the construction realm modularity is less common. Bertelsen (2005) argues that modularity within construction can aid in reducing the variation in production. The idea is to consider the building as a product, manufactured in permanent factories with support from tools and methods from Lean production. The paper emphasise the need to address modularity in construction from a functional view rather than the assembly of components.

Björnfot and Stehn (2004; 2007) state that buildability is enhanced by modularity in the design phase through fitting between elements. They conclude that a modular approach facilitates issues such as Just-in-Time, scheduling, quality and flexibility. In addition they also say that buildability is also managed during the production phase via simplified organisation of material and resources. So to summarise, there has been some conducted studies on modularity in industrialised housing but merely on a conceptual level. Modularity has potentials to lower lead times, achieve control on materials, simply maintenance and secure quality (Erixon et al. 1996). In the prolongation, by addressing these issues, production control and value capturing can be managed, issues which are prevailing in industrialised timber housing.

1.3 The industrialised timber housing trade

The high strength, low weight and manufacturability of timber have been utilised in the development of the industrialised housing trade. In this sense timber has equal prerequisites as steel and concrete to function as construction material in industrialised multi-storey housing. However, there have been unsuccessful initiatives with both steel (Open house 2008) and concrete (NCC) (Gerth 2008). These initiatives did not fail from a material point of view, rather it seems to have taken too big leaps too rapidly, in combination with impatient management, demanding immediate results. Most of the timber building systems are family owned companies where development has been allowed to take smaller steps, giving the organisation the opportunity to mature in a better pace (Höök 2008).

The trade has seen much development, but Skärpning Gubbar! (SOU, 2002) reported of the urge to address issues such as defects management and production efficiency. The sequel Sega gubbar? (Statskontoret 2009) presents rather negative conclusions with remarks such as "a sector strongly fragmented in various parts and organisations within the Swedish construction branch". The report also states that the
inclination to change is low within the trade and unclear distribution of responsibility in governmental administration.

Under these conditions, it was decided to take a closer look on the building services within the industrialised housing. Currently, there are several actors involved, including consultants, subcontractors and material suppliers (wholesalers). The building company procures these parties individually and on short-term agreements. The actors seem to remain in the traditional culture with a dispersed view on value. To be able to break this dependency, enhanced industrialised practice for the production process of building services is crucial.

1.4 Research motives

The underlying project to this thesis derives from the undeveloped area of the building services (electricity and HVAC) within the industrialised timber housing. Economical calculations from timber housing construction projects in Sweden showed that, a considerable part of the total cost originates from the procurement and assembly of the building services; shares exceeding 20% are not rare. Notable is the limited previous research within this part of industrialised timber housing.

By taking a starting point in Höök (2008), who conclude that there is still a problem regarding balancing of values between customer, performance and people it is likely that this problem is present also for the building service systems. Only some efforts have been made to approach the value concept in industrialised housing, see e.g. Björnfot (2006). Further, Höök (2008) states that there is lack of standardised work and routines and a lack of work practices necessary to facilitate a smooth production flow. These conclusions points in a direction of poor production control. Also in this case, it seems likely that the problems are valid for the building services. To summarise, these observations show that there is a need to address the concepts of value and production control of industrialised housing.

Modularity is proposed to have characteristics to facilitate the move towards the desired state in Figure 1b. Moreover, there is a clear scientific gap where modularity has not been fully explored within construction research in general and the industrialised timber housing in particular.

1.5 Thesis aim and scope

The purpose of the research is to:

Evaluate the feasibility of modularity for building service systems within industrialised housing in Sweden.

The term feasibility comprises investigation of how value management and better efficiency of the production via enhanced prerequisites for production control can lead to improvement. Evaluation of the feasibility of modularity is done in respect to standardisation, why the viewpoint of Lean in respect to modularity is utilised. The purpose is also set outgoing from the scarce number of scientific results concerning modularity within construction. In order to properly reach the overall purpose a subset of research questions have been developed:

MODULARITY IN INDUSTRIALISED TIMBER HOUSING
Question A: How can modularity enhance value for building service systems within industrialised housing?

Question B: How can modularity create prerequisites for production control for building service systems within industrialised housing?

Question C: What are the characteristics of a building service modularisation (products, processes and supply chains)?

1.5.1 DEMARCATIONS

The industrialised timber housing industry has been developed rather rapidly in recent years. This thesis only looks at how the building services can be modularised, not technically optimised. In order to increase the level of industrialisation it might, in the future, be interesting to investigate whether the structural systems can be divided into modules as well.

Further this research only considers the adaptation of building service modules within the industrialised timber housing industry. There is a possibility that a well-defined modularisation can be of interest to other construction sectors as well, however that will not be included in this research.

Also, the thesis only looks on the industrialised timber housing industry on the Swedish market, which means that local conditions are applied, i.e. the Swedish building code is followed (EBR).

To understand modularity in industrialised timber housing context, only lean theories no other theoretical fields are used. Lean and modularity are influenced from different theories, methods and tools, such as Total Quality Management (TQM), Supply Chain Management (SCM) and Value Management. These fields are not included in the theoretical frame of reference.
1.6 Thesis disposition

The thesis consists from two parts where the first part is the cover paper including Chapter 1-7 listed below and a second part comprising two appended papers. The contents of the cover paper are:

Chapter 1-6:

Chapter 1: The chapter introduces the reader to the research field. This is followed by the aim and purpose of the thesis.

Chapter 2: The chapter presents the chosen methodology for the research and the different methods for collection of empirical data analysed in Paper I-II.

Chapter 3: The chapter gives the reader an overview to industrialised housing and the terms and conditions for building service systems.

Chapter 4: The chapter presents the theoretical framework of lean and modularity for the thesis and presents a model of analysis for investigating the empirical data.

Chapter 5: The chapter presents the empirical results from Paper I-II collected in five conducted case studies. The data is analysed with support from the proposed model of analysis in chapter 4.

Chapter 6: The chapter gives conclusions from the findings in the analysis and Paper I-II, including a visualisation of the proposed modules, in relation to the overall aim of the thesis. This is followed by a discussion of the findings and their validity. The thesis is concluded with a section of suggested future work.

Appended papers I-II:

Paper I: *Lean Modular Design: Value Based Progress in Industrialised Housing*

Written by Martin Lennartsson, Anders Björnfot and Lars Stehn, published in Proceedings of the 16th Annual Conference of the Intl Group for Lean Construction, July 16-18 2008 Manchester, UK. Martin Lennartsson’s contribution was planning, performing and evaluating the case study. All authors contributed to conceptual ideas for the Paper. The paper was written by Martin Lennartsson under the supervision of the two co-authors.

Paper II: *Production Control through Modularisation*

Written by Martin Lennartsson, Anders Björnfot and Lars Stehn, published in Proceedings of the 17th Annual Conference of the Intl Group for Lean Construction, July 15-17 2009 Taipei, Taiwan. Martin Lennartsson’s contribution was planning, performing and evaluating the different case studies as well as the analysis idea. All authors contributed to the conceptual idea for the Paper. The paper was written by Martin Lennartsson under the supervision of the two co-authors.
2 METHODOLOGY

This chapter will discuss the methodology of the research, i.e., aspects of the research approach and research strategy. The chapter also discuss the validity and reliability of the thesis.

Holme & Solvang (1991) argue that methodology is a tool or a way to solve problems and thereby get new knowledge. Everything that helps the researcher reach his/her goal is methodology.

2.1 Researcher's background

The investigator as human instrument is limited by being human – mistakes are made, opportunities are missed and personal biases interfere (Merriam 1994). The extent of the researcher's personality characteristics and skills necessary for the selected research needs to be assessed. It is not possible to conduct and analyse data in research without considering and being aware of the biases due to the researcher's background and the subjectivity of the researcher (Meredith 1998).

My background is a MSc. in Industrial and Management Engineering, quality engineering from Luleå University of Technology. A technical specialisation in civil engineering was chosen and has proven useful in this research. Previous relevant experience includes master thesis work at SKF (manufacturer of bearings). The work gave valuable knowledge about process-based manufacturing. The conditions for the work with this thesis are of course different, but a general aim for the studied branch is to become more process-orientated.

I have been involved in the Lean Wood Engineering (LWE) programme. LWE is a competence centre for research and development of industrialised timber construction, wood manufacturing and interior solutions. I have participated in workshops, seminars, courses and conferences with other LWE participants that have backgrounds from both technical and social sciences. The different activities have been important in the pursuit to gain a deeper pre-understanding of the phenomena to be studied, e.g., different theoretical viewpoints when analyzing the same empirical data and analysis from other participant's points of view. The different backgrounds have provided dynamics to seminars, enhancing my knowledge of qualitative and quantitative research. Also, companies participating in LWE have provided their experience and knowledge, providing inspiration. In all, the participation in LWE has provided me with a high level of pre-understanding for my research and has enabled me to formulate relevant research questions.

Moreover, I have been involved in TräCentrum Norr (TCN), an association aiming at strengthening the Swedish timber industry as a whole. TCN supports development in three fields, metrology and process control for customer driven production in saw mills, increased durability for outdoor wooden components and industrialised timber construction. Throughout the research project, representatives from the participating companies, me as well as other representatives from my research group, have met and taken part in related subprojects, meetings and seminars. This participation has improved the understanding of involved companies, i.e., the products they provide, their production strategies and the
methods and the context where they make their business. The learning from this participation is more of tacit nature and hence not documented. However, the improved understanding has influenced the analysis of the collected data.

The understanding of the lean concept has mostly been influenced by earlier work in the research group as well as workshops and seminars provided by LWE. A source of inspiration has been the network of Lean construction where I have participated in three annual conferences and exchanged experiences with other researchers on an international level.

In the advance of the project, the researcher has participated in a number of PhD courses. Courses closely related to the projects are Lean in practice, Marketing and Logistics and Wood, Architecture, Marketing and Industrialisation. The Lean course focused on the problems of a housing company and the design of a production facility layout outgoing from lean principles. The marketing and logistics course emphasised the importance of these fields and especially the logistics part is important in modularisation. The last course Wood, Architecture, Marketing and Industrialisation gave an overview to the evolution of timber based construction in Sweden. The courses built up the level of pre understanding of the researcher.

2.2 Research strategy and design

Yin (1994) means that all empirical research has a research design, implicitly or explicitly expressed. The research design can be explained as the logical sequence which connects the empirical data to a study's initial research questions and its conclusions. The researcher uses the design as a guideline in the process of collecting, analyzing and interpreting the observations.

The choice of research methods is based on the idea outlined in chapter 1 where the aim is met by investigating the feasibility of modularity for building service systems within the industrialised housing trade in Sweden. It is important to emphasise that, this research is based on qualitative methods. This ambition is supported by the ability of qualitative methods to give detailed descriptions of situations, events and people. It can provide information about different people's experiences, attitudes, opinions and thoughts. These are important aspects as the prevailing culture much relies on the actors.

The research design is also related to the demand for better integration of the building systems to the timber building systems and the ambition to get a systems view of the building (the product). There was thus a need to have a systems view of development, where knowledge is systems-dependant, i.e. it is important to understand the synergies between components of the system. My methodological considerations and the approach of the R&D programs of LWE, TCN and the Timber structures research group had a role in advancing a system perspective combining technical and production process related issues and integrate the case study strategy. The systems view stimulated the project and drew knowledge and backup from LWE and TCN, in which the project belongs to.

2.2.1 Case study approach

Based on the research motives and the proposed research strategy, a total of four case studies were conducted. The cases aimed to obtain a deeper understanding of the prevailing strategies and production methods within industrialised housing and
the building services trade. It is important to emphasise that this also includes identifying participants and participant relations across the whole supply chain. Yin (1994) describes the Case Study strategy as follows:

"In brief, the Case Study allows an investigation to retain the holistic and meaningful characteristics of real-life events - such as individual life cycles, organizational and managerial processes, neighbourhood change, international relations and the maturation of industries."

(Yin 1994 p. 3)

Bell (1993) means that the strength with the case study method is that it makes it possible for the researcher to focus on a particular event or phenomenon and try to find the factors influencing that phenomenon. Such processes may not be revealed in a survey inquiry, but still be crucial to the function of a system or an organisation. According to Wallin (1993), the advantages of a Case Study are that the research is carried out under real circumstances and it provides the possibility to generate in-depth knowledge about the research.

The research strategy was chosen based on the advantage of a case study where the researcher can take part of the holistic and meaningful characteristics of real events, and thus come to understand a complex phenomenon (Meredith 1998). According to Yin (1994 p.9-10), disadvantages of the case study approach that must be considered in terms of validity and reliability are:

- Ambiguous information and/or biased views influence drawn conclusions.
- Case studies provide little basis for scientific generalisation.
- Case studies can lose the grasp by expanding and thereby take too long time, hence being difficult to analyse.

2.2.2 RESEARCH APPROACH

The chosen research related to building service systems within industrialised housing is fairly new. It was therefore decided to take on a learning strategy where case design was decided depending on analysis and learning of the previous case. Thereby a general knowledge of the field is gained, relevant analyses can be made and findings can be declared as valid. With my background in quality engineering, it was decided to use the logic of the PDSA-cycle (Figure 2). The cycle consists of four distinct phases, plan, do, study and act (Bergman & Klefsjö 2001).

![Figure 2. Research approach using the PDSA-cycle.](image-url)
The idea is based on the notion that there are no a priori hypotheses, no presuppositions, and no advance theorizing. During the process the empirical area of interest is gradually developed and also the theoretical frame is refined (Alvesson and Sköldberg 2008). The approach is concentrated on finding underlying patterns and an overall comprehension.

2.2.3 RESEARCH PROCESS

The initial idea of this research was to investigate possible advantages of a general development of building service systems for industrialised housing with an aim to cut lead times and increase the industrial level in production originating from lean ideas. This approach seemed reasonable as there had been previous research projects involving industrial builders with this outset (Björnfot 2006; Höök 2008). Consequently, the core of the performed research is the building service systems in an industrialised timber housing context.

Figure 3 presents an overview of the research process in relation to the construct of this thesis. Due to the limited quantity of previous work within this research field, the strategy initially included a market survey study, which generally didn’t contribute to general research results. However, the study is important to include as it presented an overview of the market for components and systems regarding electrical installations. Consequently, the following studies could be coordinated in order to answer the overall aim of this research.

During the mapping of electricity and plug-and-play system studies, there were two companies involved in the project. The results built up a general knowledge within the field and the evaluation concluded that more support was needed and three more companies were engaged to participate in the project with a general goal to develop the building services within the trade towards a more industrial orientated practice. The new constellation of companies decided to perform a flow mapping of building services and arrange a consultant procurement competition with the purpose of generating new innovative building service systems.

**Figure 3.** The research process.

MODULARITY IN INDUSTRIALISED TIMBER HOUSING
As shown in the figure, two fields within the theoretical framework has been applied, namely Lean and Modularity from which a model of analysis has been developed. These theoretical areas have been the foundation within the two appended papers; Paper I discusses modularity from a value perspective while Paper II reviews modularity from a production control perspective. Together with the model of analysis, the overall results from all case studies contribute to the design of a theoretical model for modularisation of building services in industrialised timber housing. The theoretical model is then visualised in 3D considering basic knowledge of building services, empirical results from the different cases and the theoretical framework.

2.3 Case study descriptions

2.3.1 CASE COMPANY DESCRIPTIONS

The companies involved in the research produce a total of 3 500 apartment units annually, which correspond to a share of nearly 20 % on the Swedish market (Table 1). Companies 1-4 base their production on Timber Volumetric Elements and company 5 use elements where frames are built by massive/glulam timber. Companies 1 and 2 were involved in case 1 and 2 while all five companies participated in case 3 and 4.

Table 1. Overview of the five involved housing manufacturers. For more information refer to Paper I and Paper II.

<table>
<thead>
<tr>
<th>Company</th>
<th>Turnover (MEUR)</th>
<th>Building system</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>42</td>
<td>Volume building system</td>
</tr>
<tr>
<td>2</td>
<td>7</td>
<td>Volume building system</td>
</tr>
<tr>
<td>3</td>
<td>42</td>
<td>Volume building system</td>
</tr>
<tr>
<td>4</td>
<td>18</td>
<td>Volume building system</td>
</tr>
<tr>
<td>5</td>
<td>14</td>
<td>Element structural system</td>
</tr>
</tbody>
</table>

2.3.2 MARKET SURVEY

As the project started with scarce sources of knowledge, it was decided to start to look at the electrical system. The system demands less space, in comparison to heat, water and especially ventilation and is thereby easier to manage. A market exploration was made with focus on products and systems. The hypothesis was that better components or systems would help cut lead times in production.

The research started when NCC launched an industrial construction initiative (Gerth 2008), where the assembly for the electrical systems was solved using plug-and-play systems. The initial approach was to explore different developers of these kinds of systems. The survey included five different systems. However, three systems were discarded at an early stage, as they were developed for use in offices, schools and other public facilities.

2.3.3 MAPPING OF ELECTRICITY

As the initial approach was focused on the electrical installations and no previous known investigations had been conducted within industrialised housing, it was
decided to map the current practice at one of the participating companies. The chosen company has a production based on volumetric units. The chosen project for the study included dwellings with three to four rooms in four floors. The study was conducted with the aim to:

- Define value-adding activities in electrical assembly.
- Measure approximate time for doing these activities.

To complete this task, a video camera and a stop watch was used to map the assembly of electrical installations at the production unit. In total four hours of film was gathered. Categorisation was made of different kinds of activities. Data was collected from one project during one month, comprising 53 volumetric units.

The study also included a categorisation of commonly occurring errors in assembly concerning all building services (Electricity and HVAC). This was made by investigating records of reported errors from 14 projects and 1843 volumetric units. Following this categorisation, a selection of commonly occurring errors was chosen to analyse the additional correction time in case of erroneous assembly. Personnel from concerned work groups were interviewed in open-ended interviews, where they made estimates on the corrective time for their trade.

2.3.4 PLUG-AND-PLAY SYSTEM STUDY

The conclusion from the market survey study was to continue with a closer investigation of plug-and-play systems for electrical installations. It was decided to make a test at one of the involved companies. The chosen project consisted of a temporary one floor prison facility in a single building.

The strategy for this study was to observe the assembly both in the production facility as well as on-site where completion was made. The focus for this study was to follow the procured electricians in their work and perception of the tested system. There were three electricians working in the project. The assigned electricians followed the project from the production facility to the construction site. Activities were categorized and time measures were made in order to compare with traditional assembly. The collection of data was made with help from a video camera and a stop watch. In total, three hours of film was gathered from the production unit and the site. Following the completion of the project, an evaluation was made where electricians and designers gave their opinions about the tested system. The evaluation was designed as a focus group.

The evaluation provided the researcher with more knowledge of a plug and play system, both pros and cons which are important to take into consideration for managements if they want to invest on this kind of system.

2.3.5 FLOW MAPPING OF BUILDING SERVICES

The decision was made to continue the research project with a consultant procurement, aimed at all Swedish building service consultants. For this, it was important to work out a solid tender in order to specify system demands. It was therefore decided to conduct a mapping of building services at all involved companies. The study was carried out by investigating and analysing drawings, as well as interviews with designers from the companies. Suitable projects for investigation were decided by the companies. Then interpretations of these projects were made in respect to critical interfaces within the building.
The analysis was aided by the use of the Design Structure Matrix (DSM) that is suitable for decomposition of systems (Browning 2001). The study provided valuable information about how media runs through a generic building and also the location of critical interfaces with respect to the building service systems.

The interviews were prepared by the researcher via beforehand sent questionnaires to the involved participants. The researcher also made initial analyses from the drawings in order to have some knowledge when beginning the interviews. The design of the interview questions was verified and revised in accordance with the answers from the respondents.

2.3.6 CONSULTANT PROCUREMENT

In the progression of the project it was decided to carry out procurement for development of future building service system. The project group turned to the Swedish building service consultants. An initial phone survey was made in order to find the general interest for such a project. The response was positive and the companies decided to launch the competition. A solid inquiry was developed and sent out to consultants that had declared interest in the project.

When the time limit expired, five proposals were submitted and the consultants were invited to explain and defend their propositions in a hearing with the companies. The examination was conducted using a prepared form of questions (see Appendix 1), which was aimed at evaluating the level of a systems view and industrial adaptability of the propositions. Even though no proposal was accepted for further development, the competition gave valuable information from the different proposals as they highlighted critical areas of interest for the development of building services for industrial timber housing.

2.4 Validity and reliability

In general, validity in qualitative research is about questioning whether the right method or measurement at the right time is used, and if that leads to relevant results. This is done by describing the data used and how it has been processed, and should be conducted during the whole process. Reliability makes sure that, if a later investigator conducts the same case study with exactly the same procedures the same findings and conclusions will be drawn (Yin, 1994).

2.4.1 CONSTRUCT VALIDITY

Every situation in research is unique, and the validity has to be judged in relation to the context and the situation where each interview or observation is made. According to Yin (1994), constructing validity is especially problematic using case study design. Critics mean that case study researchers often fail to gather enough measures and that doubtful assessment are used to collect the data. Yin suggests the use of multiple sources of evidence and to establish chains of evidence. The rationale for this logic is triangulation (see Figure 4) used to find evidence for, explain, predict or understand certain empirical phenomena (Denzin 1989).
14 Methodology

![Diagram](image.png)

**Figure 4.** Multiple sources of evidence and triangulation

Archival records in form of drawings have been investigated, written reports and feedback summaries have been analysed. Observations from production units, meetings and seminars have been done and interviews have been conducted using prepared question forms as well as open ended interviews where the respondents have answered freely. To facilitate a high construct validity of the studies, multiple sources of evidence were used in the case studies through personal interviews, observations, investigating archival records and documents.

2.4.2 EXTERNAL VALIDITY

External validity is related to the possibility to generalize the findings beyond the immediate case study. Critics say that single cases often prove to be hard to generalize to a broader spectrum. In order to secure external validity, knowledge was collected from several companies. Also, the pre-understanding via participation in LWE and TCN (knowledge from numerous additional companies) and contact with the building services trade (e.g. consultants and subcontractors) provides sources for validity discussions. Validity is further discussed in Chapter 6.

2.4.3 RELIABILITY

Reliability is a measure of to which extent a certain procedure gives the same result when applied under similar conditions at different occasions. As an example, a specific question that gives one answer under certain circumstances and another answer under different circumstances is not a reliable question (Bell, 1993). Consequently, reliability aims to minimize errors and biases in a study (Yin, 1994).

If an instrument isn’t reliable then there will also be a lack of validity. However, a high level of reliability does not necessarily imply a high level of validity. A question may give the same or almost the same answer at different occasions but still not measure what was designated (Bell, 1993).

In order to strengthen reliability the researcher has used a dictating machine in order to reduce the possibility of errors in the interview interpretation. Also for some interviews, research colleagues have participated and validated the answers. In the cases with mapping and evaluation, a video camera has been used to secure that activities are performed in the same way.
3 SERVICE SYSTEMS IN INDUSTRIALISED TIMBER HOUSING

This chapter presents the settings of the studied phenomena to the reader. The framework includes the industrialised timber housing trade, building systems and business models, building service descriptions and actors and relationships in the building service process.

3.1 Industrialised timber housing

The development of housing during the 20th century in Sweden is related to the rapid industrial development. Consequently, people moved to the location of the factories, supporting a general urbanisation. This development increased housing demand in towns and cities. A historic review can be seen in the box to the right.

An important factor for the advance of the housing industry is the building code. The Swedish economy was stable during the post-war period of WWII, with a high growth (Nordstrand 2000). Already in 1947 the Swedish parliament proclaimed increased building and the construction trade took advantage of the market situation and need of new jobs. Construction was among the most expansive trades until the beginning of the 1970s.

The development of housing during the 20th century in Sweden is related to the rapid industrial development. Consequently, people moved to the location of the factories, supporting a general urbanisation. This development increased housing demand in towns and cities. A historic review can be seen in the box to the right.

Aside from the urbanisation, residence shortage depended on immigration, where the population increased with a million people in 20 years. Moreover, living patterns were altered and households became more and smaller. In early 1960s the Swedish government established the Million Homes Programme, where one million residences were to be built during a decade. The strategy focused on building of apartment blocks and mass production. The effort induced an urge for a more effective construction process with, e.g. prefabricated elements and crane assembly.

After the programme was completed in the mid 1970s, the demand for multi-family dwellings was saturated and instead a rapid growth of single-family houses was observed, derived from increased living standards and incentives of residential ownership. In this situation timber took advantage, presenting characteristics such as low weight and easy assembly. The growing demand for single-family houses resulted in closer relationships between customer and building company. The production strategy was to develop standardised prefabricated elements with flexible assembly and different solutions so that production could be internally optimised.

A governmental report (SOU, 2002) points out that the Swedish construction industry has to change in order to be able to gain control over the costs, i.e.
defects and production efficiency. Boverket (2006) suggests that one way to handle these problems is to apply an industrial practice to construction.

Figure 5. Development of the timber housing industry (the trend shown as dotted line). The vertical axis indicates the market share in percentage.

There are two systems that dominate the industrialised multi-storey timber housing industry in Sweden (see Figure 6):

- **Volume element prefabrication** – Light and massive timber frames industrially assembled to “complete volumes” in production facilities with minor on-site work.
- **Element prefabrication** – The frame is built by massive/glulam timber elements, prefabricated in factories and assembled on the building site.

Figure 6. Left: Light frame timber volumes. Right: massive timber elements. Figure modified from Björnfot and Stehn (2007).

An advantage of industrial housing is the short duration from project launch to delivery, which cuts the costs for the builder by yielding revenues more quickly. Volume element builders provide a variety of product solutions to customer segments, such as student dorm dwellings to homes for the elderly. These segments are characterised by a rather homogeneous structure and are therefore well suited for volume element production.

Figure 7 displays the total time for a “typical” 20 dwelling building project built with volume elements. Most of the production is made in factories and up to
90 per cent of the production is completed off-site. Notable is that assembly can be finished in less than four days depending on size. Interior finishing work and finishing off building services has to be done on-site and is still time consuming whilst made with traditional site-construction methods.

As stated in the introduction, the timber housing industry has verified technical solutions where the timber frame systems were developed so functional demands were fulfilled, specially solutions for sound, fire and stabilisation. In the next, still on-going phase, techniques for the tendering process and prefabricated construction methods were developed. In the third step, all technical systems (e.g., service system assembly, interior refurbishing etc.) have to be integrated with the structural system under terms of an industrial practice (i.e. use of a fewer number of components and items and controlled variations within system boundaries).

3.1.1 THE BUILDING – A PRODUCT

A product is something which has been produced by labour or efforts or is the result of an act or process. In marketing, a product is anything that can be offered to a market that might satisfy a want or need (Kotler et al. 2006). In project management, products are the formal definition of the project deliverables that make up or contribute to delivering the objectives of the project. In manufacturing, products are purchased as raw materials and sold as finished goods. A product should be functional, economically viable to produce and be aesthetically attractive (Anderson et al. 1997).

A residential building is a product composed of different systems, which are more or less complex, e.g. foundation, structural frame, interior finishing and building service systems. These components can be prefabricated to a varying extent. With a distinct production process, the building companies can focus on overall performance or make targeted efforts on specific fractions of the process. The prerequisite for this strategy is that the product – the building is well defined,
i.e. without a product at the end of the line, industrialised (construction) strategies and methods cannot be employed.

Within industrialised timber housing the aim is to view the building as a manufactured product, expected to satisfy the long term demands of the customer. This focus leads to the introduction of key words such as quality development, process repetitiveness and experience feedback. These fields of interest are important to address as a driver for industrialising construction is economies of scale, i.e. manufacturing is approaching series production and performance variables can be identified and monitored. Quality development is related to value delivery, which will be closer discussed in the next chapter. A manufacturing organisation applies other methods than project organisations to deliver value.

The manufacturing perspective challenges the prevailing working methods and the focus on the attempt to industrialise production, and the alteration it requires in relation to the traditional culture in the construction industry, a branch characterised by keywords, such as temporary organisation, project orientation and on-site construction. Consequently, a revised view on management is needed with focus on business models, organisation, competence level, logistics and assembly. Production in series can be related to the concepts of mass production and mass customisation, where the latter term refers to the ability to produce customised products with a high level of standardisation (Gerth 2008). This strategy requires a distinct standardised production process, including a high level of repetitiveness, errors occurring from poor organisation, low competence and dysfunctional logistics will cause interruptions and delays which will severely affect the overall process performance.

### 3.2 Building systems and business models in industrial housing

#### 3.2.1 BUILDING SYSTEMS

In a wide sense, the building system is a concept for technical solutions concerning the whole building. In this thesis, the building system is viewed from an overall perspective meaning that it includes the design of a whole building. When divided into more tangible parts, the building system comprises all components to a building and how they interact in the production phase as well as after the house is in operation. The building system is the cohesive link between components and production. The final composition depends on the level of prefabrication, component association, performance of additional construction components, building services system solutions and façade structure etc.

Figure 8 displays a proposal of integral parts to a building system and emphasise that it also involve parts of more administrative character, which can be connected to the business models or procurement form chosen by the building company. Englund (1979) states there are two types of building systems; open or closed. An open building system has the freedom to vary the final product as interfaces between components from different subsystems can be fitted. The closed system does not share this characteristic and its freedom is limited. The open system for on-site projects is a way to systemise technical solutions and some measurements to get a more efficient production of components.
Open and closed building systems. Inspired by Englund (1979).

Open systems suggest a sequential order of operation for the different subsystems, illustrated by the arrows. As upcoming activities in the process are not dependent on previous activities and performance, each activity can be individually optimised. Closed systems demand more interaction between the different subsystems, both technical and administrative systems as well as interaction in between, illustrated by the twofold arrows in the figure. Important to emphasise is that a closed system is characterised by the fact that components within the system have interfaces fitting to other components in the system. The building system is therefore more dependent on the company’s business model.

3.2.2 BUSINESS MODELS

According to Doganova and Eyquem-Renault (2009), there is no precise definition of business models in management literature. For example, a description of a company’s logic of value creation or how a company makes money. They propose the use of a model shaped from three blocks; value proposition (what), value architecture (how) and a revenue model, summarising the two other blocks.

In construction, the business model should be shaped after prevailing market demands, customer requirements, resource allocation, functionality, client and supplier relations and production capacity. Other considerations include trends, architectural design and plan of actions.

Actors with an open building system and a sequential order of operations are well organised for the prevailing procurement system and can for example allocate some responsibility on consultants, subcontractors, or even the client. Thereby it is possible to optimise isolated activities which will add up to the overall efficiency.
On the other side, companies relying on a closed system are more constrained by the prevailing system and have to organise responsibilities in order to optimise operation within the building system, e.g. coordination of subcontractors and JIT purchase of material. In the end, the goal is to deliver a product to the customer, i.e. a building to the client. Optimisation must be made in respect to the building, e.g. with dependencies within the building system, sub-optimisation may cause losses in other parts of the system.

The building system can be regarded as part of the business policy and consequently the relation to the building process becomes important. Figure 9 is an example of how the building process can be related to the building system. If the company only provides a technical solution, the need of commitment is little, e.g. detachments can be resolved using plaster boards; the manufacturer of plaster boards, which is at level 1, has responsibility over the function of their products but not for faulty assembly. The further down (higher level) your company exists, the more responsibility is connected to the building system. Consequently, a closed system has to contain well-defined components as it will be hard or impossible to exchange them with parts from other systems.

The studied case companies in this thesis use closed systems with much prefabrication, which press conditions to the business models. Volume element systems offer both architectural freedom and floor plan flexibility under the condition that design is made in time and is limited by the building system prerequisites. Deviations from the building system cause major adjustments and additional costs (compare open and closed systems) and is therefore not allowed.

The key for a successful industrialised project is an early communication between builder and client. If the builder has early access to the process they can influence the shape of the building. Gerth (2008) concludes that industrial builders must be fundamentally different in comparison to traditional builders with respect to organisation, marketing, production strategy, business and project processes.

According to Stenh et al. (2008) the business models rest on three parts, the offer, market positioning and operative platform, where the operative platform is most influential in the design of the business model. The operative platform is the key in the business model as it control both the offer and the level of responsibility (see Figure 9). The operative platform is mainly characterised by the building
system, the design and coordination of resources. In 2009, there are three prevailing business models in industrial timber housing, the system builder (level 3), part-system builder (level 2) and component supplier (level 1). All case companies are system builders, meaning that they adopt a holistic approach and offer and deliver complete buildings (products) to the client and in rare cases also administrating the building during operation.

3.3 General descriptions for building services

In order to find improvements within the building service systems, an overview of the current practice is needed.

3.3.1 BACKGROUND

The idea of prefabricated building services is as old as the idea to prefabricate the building. Figure 10a) depicts the erection of a three floor high building service wall using a crane. Figure 10b) is a drawing of a standardised shaft which was used in the 1970s in the final years of the Million Homes Programme (the heating system was commonly placed outside the shaft). Interesting is that electricity is not included because wire canalisation was not cumbersome at the time (simply because there was much less media installed, only power and telecom).

During the 1980s the first efforts were made to prefabricate complete bathrooms, including all necessary building services. The floor plans were often designed with the kitchen's "wet" side facing the bathroom wall in order to facilitate assembly. This gathered all building service canalisation in a shaft located in the dwellings.

In the 1990s the first system solutions emerged as shafts consistently were located in connection to the stairwell, see Figure 10c). This development was driven by new materials such as PEX (a plastic material with corrosive, pressure and thermal resistant characteristics) as well as administrator related issues. Other tested solutions included standardised ventilation shafts which were eligible for both onsite assembly and prefabrication. This system was interesting for timber house manufacturers as the shafts could be fitted into the frames. For horizontal
canalisation the building service wall was introduced, which also offered the possibility for wall assembled toilets. All the connections are placed in the bathrooms and therefore hidden but still with outside placement in the wall. In the first decade of the 2000s, building services have seen much expansion especially for multi-family houses with communication and automatic control systems. For timber buildings, the addition of sprinkler systems has resulted in allowance of more visible wood, both outside and inside of the building.

3.3.2 HEATING
A hundred years ago there were local heating systems in each room with masonry heaters, iron stoves in the kitchen and no pipe systems. Fifty years later development had led to central heating water based systems with high temperatures (+80-60 °C) where the production was made with boilers using oil, wood or electricity. Distribution was made with cyclic pumps and oversize radiators in steel. The prevailing system today still uses central heating systems and cyclic pumps for local distribution. The difference is that production is made using district heating and heat pumps. The temperatures in the systems are adjusted for different system parts. All new radiator systems are designed so incoming water does not exceed +55 °C and returning water holds a temperature of +40-45 °C.

A heat exchanger transfers the heat from the district heating circuit to the heat system of the building. With a heat pump, it is also possible to apply geothermal heat and solar energy. The advantages of water based systems are for example the ability to store heat, heat capacity, heat transfer characteristics, easy to distribute and silent operation systems. A local heating plant, in each building, should be built with separate firewalls and there are instructions, which have to be followed. For example density test protocols, pipes and components fulfill technical demands and flow charts regarding connection principles and dimension data. The distribution system (Figure 11) is built-up from pipes, pumps, shunt groups (valves regulating the flow in radiators and thereby temperatures) and connections (radiators, floor heating etc.).

![Figure 11. To the left: Pipes with connections. To the right: Shunt groups.](image)

3.3.3 VENTILATION
The system which has become more common in multi-family dwellings is Heat recovery ventilation (HRV). This system employs a counter-flow heat exchanger between supply and extract air flow. The development has resulted in better MODULARITY IN INDUSTRIALISED TIMBER HOUSING.
insulated buildings and consequently less well ventilated. Therefore as buildings urge a source of fresh air, HRV has gained ground. Different solutions are available on the market including heat exchange using earth, water or air.

The distribution of air is made with ventilation ducts and devices, supply air can either be extracted at ground level or at higher floors. The advantage of extracting air from higher floors is the air quality. The problem is that it needs some kind of device for distribution of supply air. The ventilation system is not technically complicated, but the ducts are space demanding. Consequently canalisations are made in slits within dwellings. Due to the current view on the building and structural system (see chapter 1), the ventilation system has to conform to these prerequisites. The result is project specific, customised solutions connected to the decided floor plans.

Fire
Closely related to the design of a ventilation system is a building's ability to withstand fire. Buildings with residences demand resistance for at least 60 minutes (Backvik et al. 2008) (EI 60) where E stands for integration and I for insulation. The demands originate from the Swedish building code (EBR). Ventilation shafts can either be open or closed. In cases with installed sprinklers, the class can generally be lowered by half (EI 30) (Backvik et al. 2008). The shafts can not be designed to contain combustible material.

All shaft walls should be constructed with incombustible material. Open shafts are designed with closed top and bottom in EI 60. For closed shafts, fire walls can be lowered to EI 30. In cases with mixed shafts (also including electricity & telecom), due to the increased risk of fire starting in the shaft, a detachment wall in class EI 15 must be added as well as radiation protection or insulate ventilation ducts with EI 15 (Backvik et al. 2008). Generally, there is no need for insulation of grommets through shaft walls. Insulation demands are regulated by heat radiation to other fire cells.

3.3.4 WATER SUPPLY AND DRAINAGE

Water supply
Hot water is prepared in heat exchangers located in the building's mechanical room. The pipe system should be clean and properly cut with right-angled edges. Pipes are commonly made in copper, used in its pure form or as the alloys bronze or brass. There are also pipes in stainless steel where the chrome alloy gives good protection against corrosion. Plastic pipes can be used both in buildings and foundation installations. One of the commonly used pipes is PEX which endures pressure and temperatures.

Pipes-in-pipes is a system where water pipes are placed without joints in a protective pipe. This technique enables fast detection of leakage as water will flow out via the protective pipe. Pipe grommets in walls and floors must be installed with considerations to expansion of pipes related to temperature variations. The grommets should also manage demands on tightness and fire detachment.

The life of these systems is normally shorter than the life of the building and should therefore be prepared for substitution. Visible systems will easily detect
leakages while hidden systems are secured using pipe-in-pipe solutions. Water pipe systems are, according to BBR, designed to evade noise, pressure thrusts and corrosion from high water speed. Weak systems increase these risks.

All tap water installations are required to hold a quality level of drinkable water and cold water is considered as provisions and therefore the water quality is regulated by the National Food Administration. In water installations there are risks of pollutions, e.g. precipitation of metals and growth of microbiological organisms. An issue to consider is the growth of Legionella bacteria (infect humans via respiration), which is active in the temperature interval 20–50 °C.

Drainage

Sewage includes water from toilets, water stands, tubs or other drain units. Two lands of drainage are used, self slope and pressurized systems. To facilitate sewage transport, conventional installations are designed with self slope systems with a built-in slope in the flow direction. Products and components are often type approved and include tests on density, flow characteristics and noise.

Drainage is placed either freely or by cast. Vertical pipes are usually placed freely, while horizontal pipes are both placed freely or cast in concrete. Drain pipes are made in cast iron, plastic or stainless steel.

3.3.5 ELECTRICITY

Current practice for new buildings concerning assembly of electricity includes a local plant where the high-voltage power line is connected. The central will then supply surrounding mechanical rooms with power, which in turn will supply buildings with power. Canalisation for multi-storey buildings are commonly made using shafts placed in connection to the local central. Connections are then made to supply each floor with power. Applied wires are commonly double insulated with a thermoplastic mantle surrounded with a flexible plastic pipe. Placement of wires can be done in many ways:

- Hidden or recessed installation. Wires are placed in frames of wood, sheet-metal or concrete walls or floors.
- Open or outer placement. Installations are clung or placed in pipes, edgings or canals.

Connections and joints are made using compression fittings and connector boxes.

3.3.6 SHAFTS

There are two principle solutions for shafts. Either there is a single shaft supplying the whole building and consequently much more horizontal canalisation on each floor (Figure 12a). The other solution includes multiple shafts for each 'pile' of dwellings, i.e. a shaft comprising the building service canalisation supplies the dwellings with media (Figure 12b). This implicates that the shaft connects directly to the different dwellings and avoid canalisation in corridors and access balconies.

Currently, the general practice in industrialised timber housing is that shafts are not prefabricated, meaning that all vertical canalisation and shaft assembly is made on site. Horizontal canalisation in multi-storey timber houses is consistently
assembled in the space between the ceiling and the floor element on the next floor regardless of structural system (See Figure 15, which also displays a shaft).

Figure 12. Shaft solutions seen in profile: a) Floorwise horizontal canalisation with single shaft, b) Multiple shafts with more vertical pipes and wires.

Figure 13. Horizontal canalisation between ceiling and floor element. Vertical canalisation in shaft.

3.4 Actors in the building service process
As the industrialised housing like to function within a closed system, as described above, the interaction between actors in the process become important. Therefore, this section presents the different actors in the process and the following section presents their relationships.

3.4.1 CONSULTANTS
The consultants are engaged by the contractor to design the building service systems. Hence, the consultants are responsible for presenting permitted solutions, which do not break the regulatory framework, and to develop drawings of how the different systems should be assembled. The building companies apply different strategies for building service consultants.
The building company procures the HVAC consultant and the electrical consultant separately and on a project to project basis. Therefore they have little interest of adaptation to the building system. They have little or no communication with the building company's designers or with each other. The lack of communication may lead to an absence of synchronization and lack of knowledge about the structural systems. Design drawings are delivered to the building company.

The building company has in-house employed designers concerning both HVAC and electricity, which have daily contact with designers as well as each other. Problems can thereby be handled immediately when they arise. Development projects are simpler to facilitate as the competence can be allocated in-house. Drawings from the designers can be validated and synchronized under way and after completion. It is also possible to communicate directly with the assemblers.

3.4.2 SUBCONTRACTORS

Subcontractors for the building services are electricians and plumbers doing the assembly. Some work can also be conducted by the in-house carpenters, but advanced assembly must be done by authorized personnel. As for the consultants there are two distinctive strategies for subcontractors:

- Project to project procurement of plumbers and electricians where they will be doing assembly with support from the drawings constructed by the consultants. The drawings are provided by the building company.
- The building company has in-house plumbers and electricians doing the assembly. As they are employed by the company they have direct contact with the carpenters as well as with each other.

3.4.3 BUILDER'S PURCHASE DEPARTMENT

The building company's purchase division purchases necessary material for the project. As for the building services if the company has employed assemblers they may purchase material themselves. Procured subcontractors are often bringing their own material which are part of the deal and are therefore responsible for this, but if the demand has been miscalculated they will charge the building company for the additional expense. Industrial builders are generally small actors on the construction market and are therefore obliged to purchase from wholesalers.

3.4.4 WHOLESALERS AND MATERIAL SUPPLIERS

There are different constructs for purchasing necessary material for assembly of building services. One way is, as mentioned above, to let the procured subcontractors include material in their offers. The other way is that the builder purchases the material from the wholesaler. The catalogue that the wholesalers provide consists of more than 100,000 components, which are difficult for the builder to grasp. Consequently, wholesalers have a powerful negotiation position. Important is that this state is not necessarily opposed by material manufacturers, which have good profits from the relation to the wholesalers.

The powerful position of the wholesalers is problematic; the companies may be dependent on their own purchase department, possibly without knowing it.
Discounts are based on ad-hoc considerations such as personal bonds rather than strategic market considerations. Both the builder and the subcontractors are constrained to purchase their material from the wholesaler. The wholesalers and material suppliers are also putting pressure on the consultants in order to design systems with their products. The consequence is that the consultants will provide solutions which may not be adapted for industrialised housing.

3.5 Relationships between the actors

Figure 14 shows the relationships for the two cases mentioned in section 3.4.1 and 3.4.2. Arrows in the figure show information and/or material flow within the supply chain.

The first case (Figure 14a) shows how the consultants and the assemblers have no contact with each other. This is the case when consultants and subcontractors are individually procured on short term conditions. They have no contact and drawings are delivered to the company without any synchronisation with other drawings or opinions from the assemblers. The consequence may be, e.g. difficult assembly or misplaced pipes or boxes with additional correction time. Notable is that communication is one-way, illustrated by the arrows.

In the second case (Figure 14b) consultants become part of the builder’s design team and the building service subcontractors become in-house personnel. This design provides possibilities to better communication and interaction between the different parties, which is illustrated with arrows going both ways. Problems and errors can thereby be avoided or reduced.
4 THEORETICAL FRAME OF REFERENCE

This chapter presents the theoretical frame of reference. The framework includes conducted work within the lean concept, the value concept, production control and the field of modularity. The chapter gives an insight into the theories that are applied within this research and is concluded by a model of analysis, to analyse the collected empirical data.

4.1 Lean philosophy

Taiichi Ohno created the Toyota Production System (TPS). Inspiration and ideas have been developed from Taylor and Ford with the basic idea to reduce the three types of waste, which in Japanese are called Muri (Overburden), Mura (inconsistency) and Muda (Waste).

The basic principles of TPS are how corporations should handle the issues of waste reduction and continuous improvements. The process design should run smoothly and deliver value to avoid inconsistencies (Mura). In order not to overburden (Muri) the process there is a need for flexibility within the process. Thereby waste can be avoided (Muda). According to Liker (2004) TPS addresses seven different kinds of wastes:

- Overproduction
- Waiting (of operator or machine)
- Unnecessary transport or conveyance
- Over-processing or incorrect processing
- Excess inventory
- Unnecessary movements (of operator or machine)
- Defects (rework and scrap)

Lean history

The lean philosophy and concept originates from Japan and the 1950s. After WWII the military industries were forced to change direction towards civil production. The Toyota Corp. studied western world methods of mass production and recognised that, production should be ruled by actual sale and to avoid overproduction.

Krafcik (1988) coined the lean term, when working with James P. Womack at MIT in Boston, MA. The concept became immortalised in 1990 when James P. Womack, Daniel T. Jones and Daniel Roos (1990) published The machine that changed the world. Prior to the publication, not much attention had been paid to TPS outside Japan. According to Holweg (2007) it depended on the lack of documentation from performance of TPS and low interest from western manufacturers.

Until the 1980s the fear for Japanese competition was low. Within the academic community though, TPS had earned some reputation and studies had been conducted, e.g. Monden (1983); Schonberger (1982) and Hall (1983). The oil crises in 1979 increased import, thereby threatening domestic manufacturers and consequently an urge to develop manufacturing strategies. The Machine was published in a time when western manufacturing industry witnessed how they were surpassed by the Japanese superior techniques (Holweg 2007). As for many business strategies, acceptance and understanding from practitioners are best received in the eye of an imminent crisis.
Liker also brought up an eighth waste, *unused employee creativity* (by not capturing the skills and experience from employees). Overproduction being first in this list is not a coincidence as Ohno considered this to be the fundamental waste as it derives most of the other wastes (Liker 2004).

So to summarise, Lean is an interpretation of TPS from a Japanese perspective to the industrial prerequisites, at least initially the USA, and later the rest of the western world. Even though TPS puts more efforts to standardise work and development of the workers for them to be creative and solve problems (Bhasin and Burcher 2006). In the relation to TPS, lean is regarded in the sense of Lean Production or Lean Manufacturing, which relates to the perspective of lean in the USA (Höök 2008).

Womack and Jones, two of the 'Machine'-writers, developed their ideas into the concept of Lean thinking (Womack and Jones 2003), in which they describe a more extensive angle to lean and give instructions on how lean should be implemented into manufacturing companies. In the end the ultimate goal is the transformation into a lean enterprise (also including Lean accounting where accounting is adapted to manufacturing strategies).

The strategy relies on five cornerstones (see box above). Again, the fact that value specification is first in the list is not coincidental, since if you as producer manufacture undesired products, you will soon be out of business.

Lean Construction is a concept which has emerged from lean production, outgoing from principles and ideas, but adapted to fit within the construction industry. In comparison to lean production, the construction industry has a project based view with an end-to-end design. Koskela (1992) presented a set of lean principles for application in construction. Interesting in the context of industrialised housing is the principles of reducing variability, focus control on the complete process and increasing output flexibility.

In Koskela (2000) the Transformation-Flow-Value (TFV) framework was introduced, which challenges the principles of Womack and Jones to only handle work flow in production. Koskela stresses production should be performed by using transformations of inputs into outputs where value- and non-value adding

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### Lean cornerstones (Liker 2004):

- **Specify Value for the customer** – To be able to make the process more effective it is necessary to understand the demands of the customer.
- **Identify Value stream** – The value stream is the horizontal stream in a company, where raw material is refined to products, accepted by the customer.
- **Flow** – The flow in a process is characterised by the fact that a product should always be in motion throughout the process in order to avoid queues and emerging inventories. It is therefore decide the pace in the process to eliminate potential bottlenecks.
- **Pull** – The notion of pull within lean describes that the demand rules the pace in the process. This implies shorter reaction time between customer demand and current production.
- **Perfection** – The last principle states that perfection is sought through the process. In other words delivery at the right time of a high quality product desired by the customer.
activities flow through the process striving towards the goal to create value for the customer. Much of the forthcoming research within Lean construction used this framework in the coming years (Ballard et al. 2001; Bertelsen and Koskela 2002; Bertelsen 2002) and further developed (Koskela et al. 2007).

In 1994 Glen Ballard introduced the Last Planner System (Ballard 1994) which strived towards improvements of both design and construction schedule predictability so that work is completed on time. It has been applied on both design and construction phases in projects (e.g. Ballard and Koskela, 1998; Ballard 2002) Ballard and Greg Howell also presented several papers how to implement Lean Construction, dealing with issues such as reducing variation, stabilising workflow and improving performance (Howell and Ballard 1994; Ballard and Howell 1994a; Ballard and Howell 1994b). Howell (1999) states that the essential features of lean construction include a clear set of objectives for the delivery process, aimed at maximizing performance for the customer at the project level, concurrent design of product and process, and the application of production control throughout the life of the product from design to delivery.

The project organisation is considered a fundamental part of construction; it is a natural way of doing business and delivering value (Koskela and Ballard 2006). Conversely, Winch (2006) notes that projects does not necessarily have to be best practice in delivering value for all forms of construction; for example, recurring activities are not organised properly in project configurations. 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. Emmitt et al. (2005) argue Lean construction mainly focuses on problems and issues, emerging on the site.

4.2 The value concept

As stated in the previous section, value specification is one of the cornerstones within the Lean concept. Womack and Jones (1996) say that value is created by the producer. For manufacturing companies this basically mean that value is delivered by the function of the manufactured goods (Björnfot 2006). From this perspective the construction industry is not different as the goods delivered to the clients are buildings, elements and components. However, there is a distinction between manufacturing and construction how value is delivered. Bertelsen and Emmitt (2005) state that within construction, value is delivered through a temporary production system and the result is a unique product assembled at a temporary production unit, i.e. the site.

Emmitt et al. (2005) emphasise the importance of taking on a holistic view already early in the process in order to getting everything right from the start. At least customer values have to be captured as far as possible.

Important to discuss is to whom we create value? It seems like a simple task to address that question with the obvious answer, we create value to the client or customer. The problem grows as all participating parties are included i.e. aside...
from the already mentioned groups, value for the delivery team (architect, engineer and builder) must be considered (Emmitt et al. 2005). The delivery team focus on delivering the highest value to the customer; otherwise they will find their business elsewhere. So it is therefore reasonable to make a distinction between internal and external value (Emmitt et al. 2005, Paper I). Björnfot and Sardén (2006) also state that the external value can be divided into product and process value and we end up with the following description:

- External value is the clients' value and the value which the project should end up with. External value can be divided into product value (the finished building) and process value (provides customers with an excellent experience during the construction process).
- Internal value is the value created by, and between, the participants (client, contractors, suppliers, etc.) of the delivery team. Internal value strives for an economically efficient production process generating high quality products.

Cuperus and Napolitano (2005) discuss the problem with many interested parties in construction projects having different perception on value. They identify four main parties and their main view on value:

- Client – Profitability, low risk and quick turnover.
- Manager – Reduction of interference, reliable indicators to feedback and feed forward.
- Contractor – Profitability, low dependency to other contractors, high flow in authorisation allowing him to complete his task.
- End-user – high optimisation and utilisation of the space according to his needs, market prices.

With different parties having different interests it is a difficult task to find efficient production solutions. Efficiency efforts in one end may cause conflicts in another end. So there is a risk of either optimising value to one stakeholder or compromising on all. Höök (2008) states there is a lack in focus between customer, performance and people. This imbalance is explained by Höök as an overemphasised focus on the customer, leading to less attention on performance, resulting in less interest for the people creating value to the customer. Consequently, the motivation in-house for value and flow is scarce.

The construction trade is characterised by its own dynamics and the buildings are per definition static, but act on a volatile market. This notion is valid practically anywhere, but even so, the construction industry has its own culture in the way business is made (Cuperus and Napolitano 2005). Höök (2008) and Martínez et al. (2008) states that the prevailing culture in traditional construction is also present in industrialised housing and is blocking the development. There is a lack of standardised work and routines and management is poor regarding to communicate strategies and employees demands.

The industrialised timber housing trade challenges the view on value delivery within construction as it strives toward a practice of high level of prefabrication in closed facilities (Björnfot and Sardén 2005). A proposition to handle value
management within industrialised housing is proposed by Björnfot and Stehn (2007). The product offer is, from a value perspective, a well-defined and standardised building system (a product based technical platform) based on lean principles and the practical value views of specific customers (see Figure 15). An important feature of the product offer is to determine customer demands in an early stage so that the builder is in control of the value generation process. The product offer supports a cultural change in industrialised housing, where value is central in the conceptualisation of a product (building).

Figure 15. Simultaneous consideration of internal and external values in product offer development. Modified after Björnfot (2006, p.46).

Björnfot and Stehn (2007) emphasises the importance of better integration of independent subcontractors, where the product offer enables and facilitates this development. Paper II observes that the supply chain within industrialised housing is still fragmented and consequently value management is limited, leading to inferior performance.

There is an equivocal view of value specification within construction (Salvatierra-Garrido et al. 2009), focus is mainly on value deliveries from specific activities for on-site projects related exclusively to value to the customer. Further, value can be associated with lean figures such as waste and quality but lacks a distinct connection. In the extension; this indistinctive view on value will cause problems in production, i.e. how can this issue be managed if there is no value to control or strategy to follow?

4.3 Production control

Production is the act to make products (goods and services) while control is used in a variety of contexts to express "mastery" or "proficiency". Thus production control is about gaining mastery over the production process (Paper II).

The field is mature and has developed since the 1960s, when focus mainly was on solution models for specific settings. Within the manufacturing industry, production control relies on principles such as Just-in-time (JIT), Material requirements planning (MRP) and Optimised Production Technology (OPT). Further, it consists of production planning, material coordination, work load control, work order release, and production unit control (Bertrand et al. 1990). Stevenson et al. (2005), also adds tools such as, e.g. Kanban, Theory of constraints (TOC) and Constant Work In Process (CONWIP).

For construction the situation is different as for example Ballard and Howell (1998) state; planning in construction refers to the production of budgets, schedules, specification of the steps to be followed and the constraints to be obeyed
in the execution of the project. During the project, control is merely monitoring the performance against specifications decided in the planning phase. If issues arise, correctional measures are employed to handle the specific problem. Consequently, this strategy can be summarized as project control rather than production control.

Ballard and Howell (1998) find this situation problematic and state that relying production on the planning phase will lead to coordination problems in production. Specifically, they discuss work flow uncertainty, including issues such as project objectives, work flow to production units and availability of labor and labor-related resources such as tools and equipment. The cure to deal with this uncertainty is to shield production units by making only sound assignments. In order to make these judgements, the Last Planner system of production control has been widely used and can be characterized in terms of (Ballard et al. 2009):

- Plan in greater detail as you get closer to doing the work.
- Produce plans collaboratively with those who will do the work.
- Reveal and remove constraints on planned tasks as a team.
- Make and secure reliable promises.
- Learn from breakdowns.

Other used tools to gain production control in construction are e.g., Critical Path Method (CPM), Critical chain (CC) and Line-of-Balance (LoB). As noted above, production control tools are aimed to work and function in on-site project environments. Tools with the capacity to address production control in early stages of construction (crucial in the case of industrialised housing) are Poka-Yoke (PY) and Set-based design (SBD). SBD has the possibility to be applied in early phases of construction and proactively achieve production control through an improved design process. However, as illustrated in Figure 16, there seems to be a lack of production control methods or systems that can be applied early in design to provide proactive control of production events.

**Figure 16.** Common production control methods and their relation to the construction process.

**MODULARITY IN INDUSTRIALISED TIMBER HOUSING**
Within the realm of industrialised housing it is interesting to discuss proactive production control and its counterpart active production control. Halman et al. (2008) state construction firms have to be more proactive and client-focused. Paper II presents the following description:

- Proactive production control provides control in design and prerequisites for reduced variation during production.
- Active production control strives to control occurring variation and eliminate wasteful activities.

Further, following the prerequisites in industrialised housing the concept of production control is more connected to the definition by Bertrand et al. (1990). In other words, similar to other manufacturing corporations, the management has to handle issues such as supply chain and production activities coordination and thereby achieve the goal to deliver a desired product. In addition, van der Bij and van Ekert (1999) state that "the production control system comprises a system of tasks, methods, and means, which an organisation uses to agree and maintain the availability of products to the expectations of the internal or external customer with respect to time, quantity, and place".

The prevailing culture in the industrialised housing trade is an obstacle to manage these issues. With subcontractors and consultants individually procured, optimising their own values, a fragmented supply chain is the result. In other words, the value created by the consultants is not necessary aligned with the desires from the builder and the subcontractors. As a consequence there will be uncoordinated production activities as well (see e.g. Björnfot and Jongeling (2006)).

4.4 The modularity concept

Modularity has been applied in various disciplines, such as e.g. biology (Metabolic pathways and organisms are composed by modules), cognitive science (cognitive or perceptual subsystem whose working within a specific domain independently from other cognitive systems and modules (Barrett and Kurzban 2006) and software programming (ability to add scripts to a program without altering the core (Baldwin and Clark 1997)).

Within manufacturing the driver for a development with modularity has been a complex market (Ericson and Erixon 1999), where companies are constrained to focus on specific market segments, in the chase for shorter lead times in development. Erixon et al. (1996) mention a number of possible positive effects from modularisation:

- Lead time can be lowered from parallel assembly.
Product development time is shortened, since development activities can go on simultaneously, i.e. concurrent engineering.

Capital bonding of commodities is decreased, derived from shortened lead times and lower inventories.

Material costs are lowered from reduction of articles.

Quality can be secured from testing of functions before final assembly.

Routines for tendering, planning and customer forms become efficient.

Service and upgrading is simplified with standardised interfaces, which facilitate exchange of modules.

Development of production systems is facilitated, since future goals can be broken down in phases.

However, Erixon et al. (1996) also state that modularity is not suitable for single piece manufacturing. The modularity concept has developed from systems engineering. The basic idea of systems engineering is the design and management of complex projects and resolve issues of logistics and production coordination.

Much research is also concentrated on the theme of supply chain management in respect to modularity (further investigated in Section 4.7). The logic rests on the reasoning that modular product design will influence the construction and management of the supply chain.

4.5 Modularity in construction

The application of modularity in construction is fairly new. Veenstra et al. (2006) tries to find out which modules to standardise and to define a product platform and propose better translation of functional requirements into technical specifications. Halman et al. (2008) have conducted a survey over platform based approaches within the Dutch construction industry including opportunities, limitations and restraints for an implementation. They conclude that there are opportunities but still much work has to be done. Hofmaan et al. (2009) have studied how supply chains should be matched with modular product architectures and conclude that this depends on the degree of variety in customer demand, the extent of supplier investment, dependency on supplier knowledge and the intentions of both supplier and buyer. Dawood (1996) states that prefabrication of building components offer the greatest potential for improvement of productivity and quality in building. Murtaza et al. (1993) state that the main advantages of modular construction is:

- Reduction of total project cost by 10%.
- Better working condition and better product development.
- Reduce lead time, waste, effect of weather etc.
- Increase certainty, productivity, safety, quality and shorten construction times.

In the light of the previously discussed areas of value and production control, especially product development, certainty and quality are interesting.
Björnfot and Stehn (2007) have applied the design structure matrix (DSM) to get a global view on the construction product (the building). The DSM also aided in the process to systemize and integrate design and assembly considerations. Buildability is enhanced by modularity in the design phase through fitting between elements within but also between the modules. Björnfot and Stehn (2004) have explored modularity in the quest to industrialize construction. They conclude that a modular approach facilitates management issues related to lean practice such as JIT, scheduling, quality, and flexibility. In addition, they state that buildability is managed during the production phase via simplified organization of material and resources.

Bertelsen (2005) discusses modularization in construction on a more conceptual level with a starting point in the complexity and numerous activities in an on-site project. Further, it is stated that with a modularization initiative value management will be a key issue to solve. The paper emphasizes the need to address modularity in construction from a functional view rather than the assembly of components. This conclusion means that modules should be designed in terms of functions. Consequently, module production can be assigned to specific work groups or subcontractors. This view is related to the concept of value analysis, an approach where the fundamental idea is that potential cost reductions are neglected in favor of product design. To the customer, the manufacturer’s costs represent no value and instead it is function and quality that is decisive (Andersson et al. 1997).

Jensen et al. (2009) explore modularity from a product development perspective with the aim to design a new module-based building system with support from software. CAD tools are customized to support the design of a building and in a wider sense also include CNC programming. The paper points out the importance of a well-defined platform, when designing the modules.

Voordijk et al. (2006) discuss modularity in the context of product, process, and supply chain, concluding that with proper methods, inter-organizational ICT and reversible interfaces firms will be allowed to align these three concepts of modularity.

### 4.6 Product modularity

The architecture of a product is the key to manage complexity. By breaking complex structure into smaller tangible parts, companies can regain control of the product and product-related activities. Good product architecture can be achieved with modularity.

*(Ericsson and Erikson 1999)*

The above quote summarizes the key to successful product modularization. Depending on company strategy, two different organizations providing the same product may end up with different modularized structures.

The main advantages in modularization are that the end product can vary in shape and functions, but the design and production of components and modules...
within a product family are the same (Jørgensen 2001). Several corporations have employed the modularity concept, e.g. Volvo, Sony and Xerox. Much research has been conducted with focus on product design (e.g. Gupta and Okudan (2007); Jost and Tollenaere (2005); Nepal et al. (2007)). General conclusions point out the importance of:

- Product variety. Platforms and module variant will provide a range of product variants using a small number of modules.
- Cost efficiency. Optimise costs within each module system boundaries.
- Concurrent engineering. Early defined module interfaces facilitate concurrent development of modules.

Baldwin and Clark (2000) discuss two general important ideas of modularity. First they present the idea of interdependence within and independence across modules. Then they talk about three different parts namely abstraction, information hiding, and interface:

A module is a unit whose structural elements are powerfully connected among themselves and relatively weakly connected to elements in other units. Clearly there are degrees of connection, thus there are gradations of modularity.

A complex system can be managed by dividing it up into smaller pieces and looking at each one separately. When the complexity of one of the elements crosses a certain threshold, that complexity can be isolated by defining a separate abstraction that has a simple interface. The abstraction hides the complexity of the element; the interface indicates how the element interacts with the larger system.

(Baldwin and Clark, 2000 p.63-64)

Björnfot and Stehn (2007) state that it is not the division of the product into modules that is the essence of modularisation, in construction rather it is the standardized way of thinking all through the process.

Ulrich (1995) discuss the importance of interface design and presents three different cases (Figure 17):

Slot modularity: interfaces between different components are different.

Sectional modularity: all components are connected via identical interfaces.

Bus modularity: special case of sectional modularity where there is a single component, the bus performing the connection function.

Figure 17. Slot modularity, Sectional modularity and Bus modularity. Inspired by Ulrich (1995).
The topic of module interfaces is especially important to consider when designing new modules.

4.7 Process modularity

Voordijk et al. (2006) discuss process modularity from the dimensions space and time. A process can be integrated in both time and space, either one of them or dispersed in both, where the latter view is seen as the most modular state. When production is spread over multiple time intervals or production takes place on dispersed locations, process modularity increases. For industrialised housing the time frame on-site is narrow, which increases the process modularity.

In construction, process modularity refers to management of production and establishing and controlling production methods, i.e. how the product is made (Voordijk et al. 2006). The industrialised housing trade is aiming for high degree of prefabrication, which demands a higher degree of planning and preparation than on-site building. According to Halman et al. (2008), construction firms have to become more flexible in both product and process. Björnfot and Stehn (2007) state, it is the standardisation through the process, which is the core of modularity.

Reijers and Mendling (2008) mean that process modular design has advantages such as ease of reuse, scalability and enhanced understanding. They discuss process modularisation from three aspects:

- Modularisation Operations – There are two ways to extract a sub-process, refining function and by segmentation, i.e. cutting a model in parts.
- Modularisation Prerequisites – Depending on the number of activities it can be suggested to modularise a process.
- Modularisation Selection – fragments with a single input and a single output are suitable for modularisation.

A general advantage from modular division, noted by Erixon et al. (1996) is the possibility for parallel assembly and thereby lowering lead times (see Figure 18).

Pandremenos et al. (2008) emphasise the importance of module interface definition according to assembly sequence requirements.

*Figure 18. Sequential and parallel assembly.*
Erixon et al. (1996) also note that concurrent engineering is a way to lower time for development and early defined interfaces in modules will further amplify this principle. Jiao et al. (2007) discuss the possibility to divide the assembly line into a basic and a variant line, where the basic line is used for common operations whereas the variant line assembles variants.

Further, Jiao et al. (2007) discuss the concept of a process platform, altering the focus from product platforms. This implies a commonality over the process, e.g. commonly used tools and machines.

4.8 Supply chain modularity
Voordijk et al. (2006) refer supply chain modularity to the degree of non-proximity of elements. Based on Fine (1998) they adopt the following proximity dimensions:
- Geographic proximity – Physical distance.
- Organisational proximity – ownership, managerial control and interpersonal interdependencies.
- Cultural proximity – language commonality, business mores, ethical standards and laws.
- Electronic proximity – e-mail, intranets, video conference etc.

An integral supply chain would then have a manufacturer and its prime suppliers concentrated in a geographical region, common ownership, common business and social culture and linked electronically. In contrast, a modular supply chain exhibits characteristics such as geographically dispersed actors, with autonomous management, diverse cultures and low connectivity electronically.

Doran et al. (2007) discuss the concept in terms of outsourcing strategies and emphasise that determining core and non-core competencies are the heart of supply chain modularity. Howard and Squire (2007) argue that interdependence between supplier and buyer and technical collaboration in early stages of development, more likely will result in good modular results. Lau and Yam (2005) state that product modularisation affect the supply chain design, while supply chain coordination is influenced from whether the product is innovative or conventional.

Howard and Squire (2007) emphasise the importance of collaboration and state that integration is an essential ingredient of supply chain performance. The traditional purchase model is aimed at keeping suppliers away to maintain independence and bargaining power. Furthermore, Howard and Squire (2007) argue that product modularisation leads to closer collaboration in the buyer-supplier relationship and reduction of interface constraints between modules. Through outsourcing, the quality of the modules will be a responsibility for the supplier. Consequently, the supplier will be more interested in development.

Foxon et al. (2005) approach the issue by asking: Do products design organisations, or do organisations design products? The question is important to address for organisations launching modularity initiatives, since defined settings and system
boundaries could be hard to alter and when demands shift the consequence is inefficient production environments. When analysing supply chain modularity in construction, the focus according to Voordijk et al. (2006) will be the different phases in the building process: initiation, design, execution, delivery and usage. It is concluded that the separation between design and execution is important. According to Halman et al. (2008), construction firms perceive suppliers to co-develop components, methods and standards.

To summarise, the challenge is to balance the three concepts of product, process and supply chain modularity. With an over-customised product, problems may arise in optimising the process or coordinate supply chains. On the contrary, exaggerated focus on either of the other two parts may result in a product rejected on the market.

4.9 Module Drivers

In the progression of a product design initiative aided by modularisation the translation of company objectives are not an easy task. However, a number of forces for modularisation within the product can be identified. These forces are called module drivers. Within Erixon (1996); Ericsson and Erixon (1999) and Erixon et al. (1997) a set of module drivers have been developed which have been validated through a great number of case studies. The drivers follow the entire life cycle of a product.

Product development and design:

- Carry over; Parts or subsystems that likely will not face design changes can be carried over to the next product generation.
- Technology evolution; Parts or subsystems that likely will face changes from customer demands or technology shifts. The technology itself can change or new materials are made available.
- Planned design changes; Parts or subsystems that the company intends to alter and develop. For example, changes to launch new product models, or lower production costs.

Variance:

- Technical specification; Allocation of variations to as few parts possible. It is also advantageous to do these changes late in the production chain.
- Styling; Parts influenced from trends and fashion or connected to a brand or trademark. For example, visible parts of a product connected to product identity.

Production:

- Common unit; Even though high degrees of customisation requires many variants, common parts or subsystems can be found, which can be applied over the whole assortment of product variants.
For efficient production, parts requiring the same production process are clustered.

Separate Testing: Provide the possibility to separately testing modules, before delivery to the next tier in the supply chain.

Instead of buying parts from subcontractors, some subsystems may be suitable for purchasing from vendors.

Parts exposed to service and maintenance may be clustered to form a service module. With well-designed interfaces, damaged modules can be shifted quickly.

Design modules, to allow the customer to make future upgrades. For example, the product can be redesigned, functions can be added or the product performance can be improved.

Limit and concentrate recyclable material to specific modules. Thereby disassembly can be simplified.

This chapter has presented the theoretical frame of reference. The fields of lean, value, production control and modularity have been explored. The current situation for the building service systems in industrialised housing was assessed in chapter 3. The observations identified problems obstructing development (e.g. fragmentation among actors and a prevailing traditional construction culture). The concepts of value and production control have been identified, as well as key issues to solve in order to develop the building services in industrialised housing. Modularity is an unexplored field within the industrial housing trade and is proposed to facilitate the transition from a structural system centred view towards a product focused view on the building.

The module drivers (Section 4.9) are developed with respect to product modularisation. Consequently, the choice of these drivers is motivated by the aim for a product view of the building. Furthermore, Quality Function Deployment (QFD) is proposed when investigating module drivers. QFD identifies customer demands in relation to module drivers. However, Ericsson and Ericson (1999) also state that modularisation can be made with respect to the particular aim within each unique case. The choice in this case has been determined with respect to the fields of interest, i.e. value and production control. In addition, for building services the customer demands are rather basic. This motivates the approach to use case studies in order to identify influential module drivers. Also, the identified cultural problem might have caused biases by letting interested parties participate.
The proposed model of analysis (Figure 19), utilises the general set of module drivers as was proposed by Ericsson and Ericson (1999). Through this model of analysis, the case results are analysed in three steps:

1. The gathered data observations are investigated in relation to the module drivers, presented in Section 4.9.
2. Influential module drivers are assessed based on how they facilitate value generation and prerequisites for production control.
3. In a cross-case analysis, descriptions and actions are extracted, which facilitate value and production control.

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<tr>
<th>Module Drivers</th>
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<th>Production Control</th>
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<td>Internal</td>
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In other words, the model can be viewed with modularity as the engine, whereas value and production control is the fuel bringing the development forward, i.e. these concepts provide a bridge to bring the industrialised timber housing industry closer to a product view on the building.
5 CASE STUDY RESULTS AND ANALYSIS

This chapter presents results from the performed case studies. Analyses of the cases are made in connection to the model of analysis and finally a cross-analysis. Closer motives for the case choices are presented in the Method chapter.

5.1 Market survey

Two electrical systems were in focus. In addition, a few more suppliers were investigated, but were ruled out at an early stage as they mainly provided systems for outside assembly in offices, schools and shopping malls and the other two systems had some previous experience from industrial housing. Initially, contact was established with phone calls but it was later decided to invite salesmen for the systems for presentations in detail.

Supplier A; Plug-and-play system

The exploration started by contacting the system supplier of NCC Komplett, a Swedish industrialised housing initiative (Gerth 2008). Their system has previously been practiced by building shed manufacturers. The system comes with locks so plugs cannot be disconnected after assembly. They provide complete systems including wires and centrals. The salesman stated that industrial housing was an interesting segment for this kind of system and also emphasised that they were developing software to facilitate design. 2D design files are compatible and could be altered to include connection points, centrals and sockets based on their system. A feature with this software is that it will result in a priced list of necessary material.

Important to notice is that the system needs to be able to monitor at connection points and box connections, this is a weakness within the context of industrial housing, i.e. in dwellings, installations are mainly assembled recessed. According to the salesman assembly times could be cut with 70% with the trade off with increased material costs of up to five times. The initial design costs would increase as cable lengths had to be measured precisely. Over time this cost should decrease by using standardised lengths. Another incentive for this system is the lower level of waste, in terms of material as all cables are delivered in standard lengths.

Supplier B; Plug-and-play system

This system was marketed as flexible and component and system parts should be able to move without causing any troublesome power failures. The system had been used in shopping and office complexes and was promoted to lower assembly times with 60%. It includes plugs, wires, distribution boxes and armatures, but no central units, as the main focus is offices and shopping malls where centrals are complex.
The salesman meant that the need for inspection in connection points were ambiguous, it had already been approved at one industrial builder by the Swedish electrical safety board. If a risk analysis was conducted and as long as safety could be assured there should not be any problems.

5.1.1 ANALYSIS MARKET SURVEY

Separate testing
The ambiguous view on the demand for inspection is also brought forward in Paper II and pinpoints an important issue, as it shows there is an equivocal view on the regulations. If the tightness of plugs could be verified, it would impose more responsibility to the builder. Consequently, previously unauthorised personnel may be more involved and better coordination of work groups is possible to facilitate internal values and production control.

Purchasing
The software, provided by one of the suppliers, is a way to secure the material need for a building. The objective from the supplier's angle is to ensure the builder to purchase their products. Thus, material use can be standardised. In a modular context this is proactive action for production control.

5.2 Mapping of electricity
The selected project for the study included 40 dwellings. The project was rated as quite complex and each dwelling generally consisted of four volume elements. The current practice is described by:

Boxes for sockets and switches are assembled in the wall elements (Figure 21); flexible pipes are connected to the boxes and pulled to the top of the element and finished off with a connector to join on the ceiling. If possible assembly in outer walls is avoided. These activities are performed by the in-house carpenters.
In the ceiling element, the different connections coming up from the walls should be connected in boxes (Figure 21). There is no electricity in the floors, besides rare cases including floor heating systems.

The consequence of this method is that the ceiling element becomes crucial in the electrical system assembly. Therefore, the connections on the ceiling are conducted by procured electricians. After the volume is assembled, all the connections are made by the electrician. The next step in the process is to assemble all the wires in the different boxes, followed by completing the assembly with installations of sockets and switches. These activities are carried out by the electricians. The different activities are presented in Appendix 2 and show all the activities and their approximated time including an estimated margin of error. Most of the activities vary between 1-3 minutes in assembly time.

To exemplify what this means in a global context, a comparison was made between two volumes with different complexity in the studied project. The example compares a simpler, living room volume, with a more complex, kitchen volume, for full presentation, see Appendix 3. The difference in assembly time was 49.5 minutes. The natural conclusion is that complex volumes are more time consuming. The total number of activities in both volumes was 49 respectively 82 and the total assembly time was 104 and 153.5 minutes respectively.

In conjunction to the mapping and flow overview, a study of drawing errors was made. The study comprised 14 projects from early 2006 until late spring 2007, including 1843 volumetric elements. 407 errors were reported and 237 were related to the building services, 140 for electricity and 97 for HVAC respectively. The production pace is 8-10 volumetric units per day depending on complexity and the activeness on the production line is generally as follows:

- 5-6 Electricians
- 3 HVAC-contractors
- 2-3 Carpet assemblers
- 4-5 Painters
- 15-20 Carpenters (In-house personnel)
A categorisation was made with respect to the type of error. First is a categorisation for both electrical and HVAC related errors:

- Error in measurement, wrong measurements on drawings.
- Error in quantity, missing holes or boxes on drawings.
- Dimension error, for example reversed drawings.
- Miscellaneous errors, e.g. sloppy drawings.
- For electricity, pipe errors (e.g. wrong sort) were also identified.

Figure 22 gives that measurement related errors are most common for both electricity and HVAC.

In Paper II, five of these errors were selected in order to investigate the consequences. The errors were discussed together with concerned working groups (electrician, HVAC-contractor, carpet assembler, painter and carpenter) and the results can be seen in Paper II, Table 3. The evaluation proves it is crucial, where in the production process the error is detected. Higher levels of completion yield difficulties to correct the errors. There is also a probability, that subsequent volumes share those errors, i.e. systematic errors. If the concerned volume element has proceeded too far on the line, errors are left without correction and managed on site.

5.2.1 ANALYSIS MAPPING OF ELECTRICITY

Common Unit

The case company has started up an initiative to employ a system based on common unit logic. The idea rests on the reasoning that only a standardised set of
allowed solutions for box assembly is used, i.e. a solution is provided with a number and the drawing only specify the number. The carpenter then follows the prerequisites for this particular solution. The possible gain is to eliminate faulty assembly by only allowing a standardized set of activities. Consequently, proactive production control can be achieved.

Notable is that pipe related errors may depend on usage of the wrong sort of pipes, which is also brought up in Paper II as a problem to gain production control. A solution is to use standardized pipe dimensions, which cannot be faulty assembled.

Process/Organisation

There is a lack of holistic view on the electrical assembly process. Therefore, the suggestion is to isolate electrical related activities in parallel production process. This driver was also presented in Paper I in terms of possibility to outsource the production. The observations reinforce the view of disintegration of the building service systems in relation to the structural system and more important to the building. Furthermore, the narrow view makes it hard to coordinate the activities. With an isolated process, coordination of activities will be facilitated, for better management of internal values.

The lack of coordination and the large number of activities also influence the active production control of the process. By isolating the process, efforts can be made to coordinate the activities for production control, and in the extension also reduce the number of activities. Paper II discusses the balance of on-site and off-site assembly in order to optimize the process performance and gain production control, i.e. on-site assembly requires much coordination, while high levels of prefabrication needs more planning.

Separate Testing

The driver will facilitate internal value by avoiding interruptions in production. The idea is to verify quality by tests, i.e. validation of drawings before they are delivered to the production unit. Furthermore, key parameters, (e.g. critical tolerances) in production should be identified and tested before the elements are passed on. When interruptions occur, work groups will have troubles to plan their work.

Closely related to this issue is elimination of faulty assembly. When faulty assembly occurs, production control is lost, as correctional time consumption predictability is difficult. The errors occur because of unverified drawings are delivered to production. Work groups may be reassigned from their current work tasks to correct the errors. This leads to irritation among the craftsmen. By testing the elements, the craftsmen can be ensured of the quality and can plan their work accordingly.

Purchasing

The influence from purchasing originates from the issue of unverified drawings. As noted in Paper II, the building company purchase the services from consultants and
subcontractors, a fragmentation can be identified between the actors in the process. By isolating the process and modularise with respect to the function, i.e. electrical system, better integration can be achieved between the involved actors, which will facilitate capture of internal values. In this sense, purchasing is referring to the clustering and coordination of human resources, rather than material planning.

5.3 Plug-and-Play system study

The chosen object to study was a prison project consisting of 20 volume elements. The project was quite simple in terms of electrical installations, as there was not much recessed assembly. The distribution could be made using cable racks in the corridor. Figure 23 shows an excerpt from a floor plan of the prison. The figure includes seven volume elements. To the left, below the mechanical room, is the entrance. The building is symmetrical, so it continues to the left of the entrance. The chosen system for the study is from supplier B in the market survey study.

![Floor Plan](image)

*Figure 23. Excerpt from the floor plan.*

The plugs on the distribution box were coloured in black, but the system could provide other colours as well, with the motive to avoid faulty assembly. The system was used for the power supply, emergency lighting and electrical heating system. Due to the special conditions following projects of such nature as a prison, there is no water-based heating system and also the building was not planned to be permanent. Excluded for the same reason was the alarm system.

The project initially had problems with material deliveries. The cause was related to the short period, from the design to production. With a plug-and-play system, all lengths are predetermined. Therefore, material is assigned to a specific
project, in contradiction to traditional purchasing, where material is continuously
provided.

Time measurements were made on the connection of wires to box, which
took about four times longer than to do the same operation for the plug-and-play
system. Figure 24 shows these two cases.

Figure 24. To the left: Connection of wires to box. To the right: Connection of
plugs to box.

Following the closure of the project there was an evaluation of the plug-and-play
system. The company stated that the motive for the system was potential time
savings. The company had a short production line, and other subcontractors need
access to the volume elements and if the time for the electricians were cut, the
work environment would improve.

The electrical designers were generally positive, to the development using
plug-and-play systems, but had problems of understanding the building system, i.e.
how to design with a volume-based building system. Some problems were
mentioned, for example the canals were too narrow and there was not enough
space to assemble both boxes and plugs. Future designs should block this problem.
The company management saw possibilities to extend the use of the system and
thereby reach repetitiveness within and between projects.

The electricians took a more negative stand to the system, stating it would be
better to use more conventional assembly methods. They were worried about the
connection points between plugs, saying there was a risk for short circuits
occurring from pin errors. Aside from including material costs, they admitted that
it was possible to save time in assembly. Further, their opinion was that the system
had some applicability on simple projects, but as complexity increased, it would be
difficult to find an efficient practice. The electricians said that, there was a risk of
faulty assembly when connecting wires and plugs, since connecting plugs with five
poles are reversed. A problem was that the colour system did not work as delivered
material was mismatched. Instead they proposed a bus-system, where fewer wires
are needed and several units can share cables and is controlled with digital codes.
5.3.1 ANALYSIS PLUG-AND-PLAY SYSTEM STUDY

Process/Organisation

The electricians had negative attitude derived from the current state in the trade where subcontractors work isolated and do calculations on single projects using piecework debit. Within the prevailing culture, competence is bound to the subcontractor and there are no incitements for the electricians to push the development as they possess the competence. Consequently, the builder is dependent on subcontractor competence, which reinforces their power.

The influence from this module driver is motivated by the logic where an isolated process will be easier to integrate as focus will be on a single system. Thereby the builder can exercise pressure on the subcontractor. The system proved to have some potential of time savings and gains can be found for internal value generation in terms of better coordination of the different work groups.

Purchasing

Paper II proposes this driver for production control in terms of narrowing the set of allowed material. Predetermined material dimensions are decisive in order to gain production control. The reasoning rests on observations from the case, where material purchase is made on project specific basis rather than continuously. The problems with delayed and even erroneous material delivery were also discussed in Paper II.

In Paper I the problem with powerful wholesalers was discussed. With the purchase strategy mentioned above, the builder will take control over material and shield from the wholesaler catalogues exceeding 100,000 components, which is naturally a risk for production control problems. Components from a single system will shield against mixing of parts from different manufacturers, with the risk of e.g. short circuits.

Similarly to the analysis in the mapping of electricity study, purchasing can be considered in reference to clustering, integration and coordination of human resources rather than material planning, which is a possibility with respect to the peculiarities of the construction culture, i.e. procurement on project rather than on process basis. The integration is suggested to have positive effects on proactive production control.

5.4 Flow mapping of building services

As the strategy was to find trade common solutions it was important to characterise the current systems. Consequently, a mapping of the building services was conducted with the aim to find crucial areas and interfaces in a building. The tool DSM was used to make the investigation. The case has been investigated in both Paper I and II.
5.4.1 ANALYSIS FLOW MAPPING OF BUILDING SERVICES
Initially, the idea was to gain understanding of the building service systems, which is presented in Paper I. In Paper II the analysis was extended to find critical interfaces in the suitable for modular division in order to design modules. Furthermore, as concluded in Paper I, the idea of this strategy is a trade common development, where the designed common unit modules will fit in a generic company specific building system. Thereby internal and external values can be captured and managed (see Paper I, Figure 5), i.e. well-defined common modules can be standardised in order to facilitate internal value and then the different companies are able to make individual adaptations to provide external values to their clients.

Common unit
The findings from Paper II point out Shaft, Traffic Volume and Basement as critical areas with many media interfaces. The suggestion from Paper II is to develop shaft and inner ceiling solutions (modules), which can be prefabricated.

5.5 Consultant procurement
The incitement for the consultant procurement was to find out if it was possible to detect system solutions of building service systems for the industrialised housing trade (see Paper I). The consultants were judged to have necessary technical skills. A thorough inquiry was developed. The box below presents the extent of the task.

Of the contacted consultants, a majority was interested, but had to decline with respect to work load.

Paper II presents the results from the procurement, that none of the five submitted proposals were accepted for further development. In the following sections, the proposals will be presented (one firm withdrew their offer). They will not be presented in full, but a short overview is given and then important remarks and principles, with respect to modularity, are bulleted.

5.5.1 PROCUREMENT DESCRIPTION
The task aim at 'industry adapting' building services for residences in multiple floors, using prefabricated components. The systems can be integrated to the structural system in factories or assembled on-site. With this adaptation as foundation, systems should be able to develop to fulfill future demands on energy efficiency (a demand which was also brought up in Paper I).

It is functioning solutions from the current systems that is requested – not untested ideas. It is still water based heating and 240/400 V electrical systems responding to dwelling provision.
Solutions should fulfil demands from the building code and other applicable regulations.

Mandatory:
- Heating, water-based
- Hot and cold water supply
- Drainage
- Extract air system (often with recycling)
- Electricity, power supply and light, 240/400 V
- Telecom, TV, Com and control equipment

Optional:
- Sprinkler system
- Supply air system
- Heat recovery

Evaluation Criteria
- Functionality – Fulfil comfort demands and simple operation and maintainability.
- Buildability – Integration to building system.
- Flexibility – Appliance of standard components that admit flexibility in design and shape of the building and the dwellings.
- Perfectibility – Stricter demands on energy efficiency are expected, affecting both building services and building systems.
- Potential for industrialisation – The possibility for manufacturing of components, giving cost efficient solutions (material and assembly).

Proposal 1
The proposal covered electrical systems. Valuable viewpoints and remarks are presented below.
- Time consumption is the main obstacle, the prevailing system with piecework is not efficient.
- On-site assembly cannot be eliminated but possible to simplify.
- The consultants emphasise the problems with regulations. Building companies should be able to lobby against The Swedish National Electrical Safety Board, as responsibility is moved closer to the builder.
- Mixed configurations with electricity and water supply are advised against, since leakage problems cannot be guaranteed.
- Suggestion of wire drums, which are unplugged and can just be rolled out on-site.
- Main issues to find cost-effective solutions for space requirements, purchasing and assembly times.
- Industrialised housing should be able to lower the number of components. The wholesalers are dependent on large catalogues.
- The logic for purchase must be revised, i.e. Builder-Wholesaler-Manufacturer.

MODULARITY IN INDUSTRIALISED TIMBER HOUSING
Proposal 2
The proposal covered ventilation systems and discussed upcoming future issues concerning energy efficient solutions.

- The importance of measurement devices and improved heat recovery solutions with higher efficiency was emphasised.
- The space requirements for supply air and extract air ducts in larger buildings is important.
- Preheating the supply air is an option to consider.

Proposal 3
The proposal covered ventilation and water supply, but no electrical systems. The consultant argued that electricity is rather simple to solve. The proposal was worked through and included several interesting solutions and remarks.

- Rotating heat exchangers for supply and extract air and sprinkler system. The sprinkler solution lowers the fire demands, for example allowing more visible interior wood.
- Preheating of supply air, since the insulation of buildings nowadays results in lower demand for heating. Then supply air can be distributed from the inside of a building, i.e. supply air must not be distributed under windows. Consequently radiators can be positioned on inner walls.
- Gathering of all incoming media in a volume element, which can be characterised as a traffic module, which distributes media to other parts of the dwelling.
- Shafts can be prefabricated and even integrated in the traffic module but it will reduce the available space in the dwelling.
- Separated pipes for cold and hot water in shafts, to lower the risk for growth of legionella bacteria.
- Preparation for upgrades, e.g. heat sources and ventilation units.
- Ability for integration in generic building systems.
- Identified critical parameters; procurement boundaries, module interfaces, shafts and construction tolerances.
- Modules should be able to be produced in parallel processes.
- Maintenance is facilitated through access from public areas.
- Equivalent assembly across the building yields simplified material purchase.
- Better integration with design provides better coordination and standardisation.

Proposal 4
The proposal was more on a conceptual level, rather than providing specific solution for building services. The proposal has a distinctive reasoning from theories of modularity.

The firm is currently developing a building system and the idea is to integrate the building service systems. It is based on glulam timber elements and should be
adaptable to specific modules. The consultants have developed a number of module drivers for the building services.

- Vertical and horizontal interfaces.
- Connection vertically between modules, adaptation and tolerances must be considered.
- A set of standard modules should be offered. Interfaces are designed after module driver specification. Some pipes can be plugged and activated if the building grows taller.
- Shafts consist of standardised parts, which together shape the shaft. Manufacture with sheet metal profiles.
- Design of standard dimensions, physical measurements is an important module driver.
- Software for design — in order to avoid prohibited solutions.

5.5.2 ANALYSIS CONSULTANT PROCUREMENT
The main motive to reject all submitted proposals was the lack of a systems view (Paper II), since none of the proposals contained all specified systems. The analysis of the procurement aims at reflecting the observations and analyses of the other cases. First, previously detected module drivers will be verified from observations in the different proposals. This is followed by a presentation of module drivers, which have been found from interpretations of observations within the proposals. Notable is that proposal 2 did not contain any valuable information. Furthermore, proposal 4 was based on modularity logic, which can be seen as a validation of the theoretical course of this thesis.

Common unit
The importance of vertical and horizontal canalisation was mentioned as key areas to solve, i.e., solutions such as building service shafts and ceilings seem like a feasible path. This observation reinforces the results from the Flow mapping study, where these interfaces were detected in the analysis.

As stated above, the consultants can be seen as modular entities. Their characterisation can also be related to the common unit driver. This logic is derived from the state where design is required in all projects. The problem is the adherence (interface fitting) to other modules (other actors, e.g., designers and other consultants).

Process/Organisation
Important notes like, the prevailing culture with piecework is an obstacle and the possibility for parallel production, were mentioned. The culture issue has been discussed in conjunction with the plug and play study. The suggestion of parallel production is in line with this driver, with an objective to isolate the process and thereby facilitate internal values and production control.
An isolated process will be able to balance the level of on-site assembly, which cannot be eliminated but should be able to simplify (Paper II). Better integration with design will facilitate coordination of activities and standardisation.

Separate testing
One firm suggested that, building companies should be able to lobby against The Swedish National Electrical Safety Board, to move responsibility closer to the builder. Progression in this direction will allow builders to coordinate their production better, as some activities are not bound to a specific work group or subcontractor. The statement is in line with the findings from the market survey, where ambiguity of responsibility was a concern. Further, in Paper I regulation was mentioned as a driver to consider, but in an energy saving context. However, the issue is related to the same reasoning, to be independent from alterations in regulations.

The procurement result shows that, consultants commonly work individually, without coordination. This is a modular approach, but as stated above the procurement was striving towards a system solution. Therefore, it can be concluded that it is the fitting of interfaces that fail, i.e. the system boundaries are not able to adhere to the interfaces of other required systems. The observations highlight an essential issue of modularisation, interface fitting. Interfaces do not necessarily have to be physical, as there are boundaries between actors and activities. The current state can be recognised as different parties having different interests. Efficiency efforts in one end may cause conflicts in another end. So there is a risk, to either optimise value for one stakeholder or compromise on all.

The problem has emerged in both the mapping of electricity and the plug and play studies. The unverified drawings, which cause delays, can be interpreted as poorly designed interfaces. The protective stand, which the electricians exposed in the plug-and-play study, shows how they only seek maximisation of their own values, i.e. maximising profit. As a consequence, internal values will be difficult to capture and in the prolonging production control is lost. It would be interesting to investigate and develop functions to test the transitions (interfaces) between actors. A suggestion is the application of software with built-in design rules, which will prohibit consultants and designers to interfere on respective area. In the progression, the use of a database can facilitate the use of updated drawings, which can be synchronised. In the extension, valid drawings will provide proactive production control.

The proposal based on modular principles, emphasised the importance of interface fitting and tolerances. These elements are key issues in order to gain production control. Key tolerances are subjects for testing. An example of such tolerance is the transition between shafts and volumetric units.
Purchasing
The suggestion of simplified material purchase will lower the number of components. The idea emerged in the market survey and the plug and play study. As a consequence, in conjunction with Paper II, shielding against the wholesalers (a problem brought up in Paper I) will be possible and purchase can be made in so-called black boxes. Positive implications from this is improved production control from using only standardised sets of material with specified dimensions, lowering the risk of faulty assembly and risk of leakage when the building comes into use.

One of the proposals also mentioned the importance of procurement boundaries, which can be related to the unverified drawing problems and the fragmentation between actors, previously discussed in both the mapping of electricity and the plug and play studies.

Technical specification
Radiators allowed to be positioned on inner walls, simplify canalisation of ducts and pipes. With a lower number of activities, work can be coordinated and facilitate internal values. Further, the simpler canalisation will provide enhanced production control. The placements of radiators also serve external values with better temperatures on supply air.

In the design considerations should be made in respect to separated pipes for cold and hot water in shafts, to lower risk of legionella. This can be seen as an external value.

The idea where some pipes can be plugged and activated if the building grows taller will offer different additives. Thereby, external values can be changed accordingly, i.e. additives will provide new variants with little adjustments of the production, leading to better facilitation of internal values and in the prolongation also production control.

Service and maintenance
One proposal had the shaft designed to be accessible for maintenance and service from public spaces. This solution enhances external values, when the building has come into use, i.e. service technician do not have to do plan work in accordance with desires from residents.

Upgrading
The building service systems are undergoing development and demands on energy efficient systems will become effective. Demands from rules and regulations can be seen as external values. Preparation for upgrades, e.g. heat sources and ventilation units, are therefore included in one of the proposals.
5.6 Cross-analysis of the studies

A market survey and four cases have been conducted. The collected data have been analysed with the model of analysis, based on the theoretical framework of reference (Figure 19, p. 43). The Consultant Procurement has worked as verification of the data collected in the other studies, but also three additional drivers emerged in the analysis. In Figure 25, a summary of the analysis is presented. In the table, descriptions and actions are presented, which enhance value and production control provided by the different influential module drivers.

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<th>Module Drivers</th>
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<th>Production Control</th>
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<td>Common Unit</td>
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<td>Validation of drawings</td>
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<td>Process/organisation</td>
<td>Coordination of activities</td>
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<td>Process isolation</td>
<td>Level of prefabrication</td>
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<td>Outsourcing option</td>
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<td>Standardised material</td>
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<td>Simplified assembly</td>
<td>Customisable interior design</td>
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<td>Improved accessibility</td>
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<td>regulations</td>
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<td>Upgrading</td>
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Figure 25. Theoretical model to modularise the building service systems within industrial timber housing.

The first four module drivers (4MD) in Figure 25 have emerged in several cases, while the final three are only collected from the procurement case. Notable is that all of the above stated drivers were found in the procurement.
The set of module drivers, which have been used to analyse the collected data follow a logical order in the life cycle of a product. The 4MD are all categorised in the middle of the cycle referring to production, quality and purchasing. The additional three drivers that were found are located in proximity to the others. Furthermore, the 4MD have mostly identified influence on internal value and production control. It is therefore reasonable to believe that these drivers are focused on managing these issues. Notable is also the column with active production control, where the statements refer to standardisation and coordination of activities, which is more related to production control for on-site projects. However, even though the cases comprised industrial housing companies aiming for high levels of prefabrication that attempt to avoid production control issues early by thorough planning, there has to be coordination within the process to gain production control.

The logic for the 4MD rests on the nature of the studied unit of analysis, the building service systems and its associated actors (subcontractors and consultants). Building services provide rather standardised solutions to the end-user (heat in radiators, current in the sockets, water in the faucets etc.). The design of the cases is also influential due to the low number of external values considered, since the first three cases focused on performance in production. The fourth case had a different input and it was in this case where external values were captured.

The consultant procurement analysis might seem contradictory, where the current practice in a way is modularised, since the aim was to seek system solutions, but in the pursuit for modularisation there are always submodules, which build up in the hierarchy and in the end there is a product. With this logic the product can also be seen as a module. It is in this context the building is put in focus. With different systems acting on the same level the fitting in between is the key.
Discussion and Conclusions  

6 DISCUSSION AND CONCLUSIONS

The chapter presents discussions on the value and production control concepts in relation to modularity. This is followed by a discussion comprising the products, processes and supply chains based on the analysis made in chapter 5. Following this discussion, the research questions outlined in chapter 1 are answered. The generalisation and validity of the findings are then discussed and finally suggestions for future work are presented.

6.1 Implications for value of modular service systems

The value concept was stated in chapter 4 to be one of the cornerstones within the lean concept. The way value is delivered in construction is based on projects, with temporary organisations and different parties having different view on value. This thesis has aimed to enhance value within the industrial housing trade. The analysis identified a set of actions and descriptions to enhance value. The list mainly comprises internal values. It seems modularity within industrialised housing focus on internal value capturing. The following actions emerged as important in generating internal value:

- Interface identification
- Coordination of activities
- Coordination of actors
- Process isolation and outsourcing option
- Validation of drawings
- Improved safety
- Control of material
- Simplified assembly

In essence, when breaking down the first five, the key is to identify and design interfaces. The remainder of the list more refers to the conditions in the production environment.

So the answer to Question A is that, modularity will enhance value within industrial housing through the definitions of distinctive interfaces for components, activities, and actors. Consequently, interfaces are not exclusively physical, i.e. fitting of components, but also include process adaptation and the relations between actors in the supply chain. In conformance with the results in Paper I (industry and company development), it becomes essential to properly design the interfaces. In addition, modularity will aid to improve safety, get better control on material and simplify assembly.

With the suggested base modules, shafts and ceilings, the supply chain actors in can be better coordinated. With the option to outsource the module production, the personnel can be chosen more carefully and employed to design, manufacture and develop the modules. Thereby, the building company may focus on managing and developing the building system, in order to better facilitate internal values in
Discussion and Conclusions

other areas than building services, i.e. focusing on core-competences. The strategy is supported by Doran et al. (2007), stating that the determination of core competencies are the heart of supply chain modularity.

6.2 Implications for production control of modular service systems

Production control is dealing with the challenge to gain mastery over the production process. In chapter 4 the concept was discussed from a proactive and active angle. Within industrialised housing the aim is to have high levels of prefabrication. This strategy implies more planning of different activities, in comparison to traditional construction, where coordination is emphasised. The analysis identified a set of actions and descriptions to create prerequisites for proactive production control for building service systems within industrial housing:

- Standardisation of interfaces
- Validation of drawings
- Failure-proofing
- Level of prefabrication
- Activity reduction
- Simplified assembly
- Control of materials
- Standardised material

There are three areas within the list. The first three are related to the identification and design of interfaces. The next two actions refer to the design of the process and the final two pose that production control is proactively gained with controlled and standardised material.

So the answer to Question B is that, modularity will create prerequisites for production control for building service systems through the definitions of distinctive interfaces for components, activities, and actors. Furthermore, finding a suitable prefabrication level for simplified assembly and reduce the number of activities will facilitate production planning and consequently create prerequisites for production control. Finally, prerequisites for production control will be gained with controlled (limitation of articles) and standardised material. These domains were also detected in Paper II. There were also two actions for active production control emerging:

- Standardisation of activities
- Coordination of activities

These actions are more related to project based construction, however even with an isolated process there is a need of coordination and standardisation within the process.

The current situation within the industrialised housing trade is that assembly of building services are clustered with all other activities. There is some coordination, but the production process is sensitive for disturbances. If interruptions occur there are problems of managing these in reasonable time. The electricity mapping proved that there is a large quantity of activities in a single volumetric unit related to the
assembly of electrical components. According to Reijers and Mendling (2008) this is a reason to modularise the process.

6.3 Feasibility of modular service systems

6.3.1 PRODUCT PERSPECTIVES

The current state for building services, from a product perspective is the application of rather conventional systems, as stated in the inquiry from the consultant procurement (e.g. water-based heating, water supply, electricity etc.). However, dependent on the demand for energy savings, development will occur, especially heating is in focus with heat recovery ventilation solutions where supply air is preheated. The module design has to be made with respect to these conditions. There are also drain solutions where the heat in shower water is exchanged.

According to Erixon et al. (1996), it is important to decide the sought advantages and modularise on this basis. The modularisation in this thesis has used value and production control in the analysis of empirical data. The results point out shafts and inner ceilings as modules. The idea, in reference to the common unit module driver, is the design of base modules, which only comprise the necessary systems. The modules are then subject for additives. The purpose is both to capture external values, e.g. introduction of sprinkler systems will lower demands for fire protection, and internal values, e.g. the interfaces on the modules are able to adhere to conditions for the building systems of different companies.

The barriers for developing the modules are regulation demands, not only the future demands stated above, but also for example the ambiguity of inspection demand in joints, which was discussed in conjunction with the plug-and-play system study. An investigation is needed in collaboration with authorities to decide on allowed solutions. This also includes, for example fire protection, as the rules alter when the number of floors increase.

In the continuation, verified product solutions can be offered outside industrial housing, i.e. on-site building companies purchase modules, which can be adapted to the conditions of a general building. This reasoning follows the proposed logic from Paper I, Table 5, where an industry development is made and companies make adaptation to their own environments.

6.3.2 PROCESS PERSPECTIVES

With the design of shaft and ceiling modules, the process for building services can be isolated and better coordinated. The activities are classified and clustered in respect to characteristics. Furthermore, the process isolation opens up the possibility for parallel production aiming to lower the overall lead time, (compare with concurrent engineering). By isolating the process it is also possible to manage the used tools and machines, within the process. Voordijk et al. (2006) discussed process modularity from space and time perspectives. The narrow time frames within industrial housing, call for process modularisation. However, an obstacle to
introduce the modules for the process is that, it needs more space to be able to manufacture the modules. This problem is derived from the characteristics of the product, the building, which demands much space. In the progression, subprocesses can be designed to manage extensions to the basic modules, shaft and ceilings.

6.3.3 SUPPLY CHAIN PERSPECTIVES

The current state is also the barrier for implementation, i.e. the prevailing culture in the trade. The different actors focus on maximising own values. Consequently, subcontractors take a protective stand in order to defend the current practice, which include piecework payments. The consultants are acting in the other end of the supply chain and they close deals with several clients. With a narrowing time frame, the risk of faulty drawings increases. Furthermore, there are material suppliers, which also aim at maximising their profits. In the current state, the power is assigned to the wholesalers as building companies do not possess the necessary knowledge. With a component catalogue exceeding 100,000 articles it is difficult to grasp.

Voordijk et al. (2006) discuss modularity in this context and the importance of proximity issues such as geography, organisation and culture. With dispersions of these concerns, the supply chain modularity increases. So the conclusion is that the supply chain within industrialised housing has a rather high level of modularity. However, there is a lack of balancing values to the different actors in the supply chain, the proximity of the view on value, i.e. the interfaces between the actors are ambiguous as the actors perceive value from different angles.

Material purchase will be more focused with standardised modules and more awareness of the included parts and components. It is important to consider product development, since when production terms and conditions are set they may be difficult to alter, which is also observed by Fixson et al. (2005).

6.3.4 STRATEGIES FOR IMPLEMENTATION OF BUILDING SERVICE MODULES

The main strategies for the implementation of building service modules rely on the conducted analysis of empirical data and the discussion in the previous sections (6.3.1-6.3.3). The focus has been on finding module drivers, facilitating value capture and production control. The challenge is to find balance between considerations concerning product, process and supply chain.

- Introduction of the base modules shaft and ceiling, only comprising necessary media. The interfaces should be prepared for additive submodules.
- Isolation of the process, only comprising the necessary activities, with possibility for parallel assembly.
- Outsourcing strategy, isolation of the actors in the supply chain.
- Pointed purchase of materials, with standardised bills for the modules.

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These strategies work on a global level, following the logic in Paper I with industry and company development. The possibility to add submodules is important to include in order to locally optimising the product (the building). A key for a successful implementation is the definition and design of interfaces. In essence these strategies are the answers to Question C, to characterise building service modularisation.

The interface design is important in the pursuit to level out the dependency between the building services and the structural system, but also the mutual dependency between the building services.

6.4 Visualisations of modular service systems

Erixon et al. (1996) have identified a set of parameters that can be measured to evaluate the effect from the modularisation.

**Product parameters:**
- Quality in assembly.
- Time to develop products.

**Process parameters:**
- Lead time in assembly.
- Capital bonding of commodities.
- Assembly time.

**Supply Chain parameters:**
- Material costs.
- Logistic costs.

In the progression, the idea is to find specific variables connected to these parameters and decide whether they should be subjects for continuous monitoring or not. For example, it might seem like a simple task to measure the lead times, however it has to be decided what activity or activities in the process that are critical to the process performance.

Furthermore, the measurement in assembly needs to be thoroughly investigated in order to find what is included in the conception. An emerging measure, from the empirical data, to secure the quality was the introduction of software, which could provide bills of material based on the design and a set of design rules with connection to drawing databases, invalid drawings can be avoided.

An initial 3D-visualisation has been made of the proposed shaft and ceiling solutions (Figure 26). At this stage the visualisations are supposed to show the logic in a more figurative way. The figure has been marked with hotspots, interesting in a modular context to discuss. Ventilation ducts are running in the ceiling and have interfaces facing the different rooms in the dwelling. The placements of these interfaces should be flexible to adapt to different solutions for the floor plan. Furthermore, the media in the shaft should be coordinated with respect to buildability, maintainability and safety (elimination of bacteria growth in water pipes). Essential in the development is the definition of the interfaces between the
shaft and the ceiling. These interfaces should probably have tolerance measures for continuous monitoring, as the interface will be present in practically all product variants. Similar conditions are valid for the interface to extend the shaft to higher floors.

![Diagram of interfaces for supply air device, coordination of media, and transition interface between shaft and ceiling.](image)

**Figure 26.** Visualisation of principle solutions for shaft (Red and blue) and ceiling (Green and yellow) in a general dwelling.

It is also important to define the general interfaces for attachment of the modules to the structural system. Properly defined interfaces will increase the interest for the solution on the market.

This reasoning relies on the interfaces concerning the process and the supply chain. If the modules can be offered on the market, builders can focus on their core-competences, instead of trying to optimise process performance and
coordinate the suppliers within the building service trade. So the physical interfaces may have implications on the interfaces of the process and the supply chain.

With the proposed module solutions, may the housing industry have possibilities to move towards the state where the building is superior (Chapter 1, Figure 1b). This logic rests on the reasoning with flexible modules possessing the ability to adjust to customer demands, altered regulations and different structural systems.

6.5 Methodology and validity discussion

The methodological approach with a case study design influences the possibility to generalise the obtained results and draw conclusions, which are valid in a global context. The selection of cases is crucial in this judgement.

The conducted studies were all qualitative in its nature. Therefore, it becomes important to have multiple sources of evidence to verify the construct validity. In the market survey and the three first cases, data were collected from archival records, documents (drawings) and also through direct (mapping) and participant (meetings) observations. But in order to triangulate the data the strategy was somewhat unusual with the employment of a procurement competition. The submitted proposals in the competition can be seen as answered surveys and the hearings as open ended interviews.

The research does not include parts of construction aside from housing. However, the trade generally has a project-based approach and it seems likely that the cultural obstacles are present across the industry. The validity of the observations from the consultant procurement should be rather strong as the proposals were developed with own investments and there was also incentives for payments if the proposals had been accepted for further investigation.

Within this research, the approach was to apply a learning strategy analogous to the PDSA-cycle originating in quality engineering. The choice was motivated by the immature field of research (building services within industrialised housing), as well as the background of the researcher. When reflecting over the achieved results, it can be decided that the design was suitable when considering the choice to study value. The prevailing culture and view on value imply biases on the different actors’ perceptions. With a learning strategy is it possible to design the next case accordingly. Then it is possible to see phenomena from different angles and generic conclusions can be drawn.

The external validity is connected to the possibility to generalise the research results outside the boundaries of the immediate case studies. For this research, it can be concluded that the external validity is strengthened by the participation of five different industrial building companies, which have agreed on the case study results. In addition, similar stands were taken by different participating consultants in the procurement, which show how the trade views this problem. The design with the procurement as a case to validate data is also reinforcing the validity of the data.

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6.6 Future work

The theoretical fields within this thesis are modularity and lean. The lean concept has been present as a development enabler within research of the industrial housing for quite some time now. The efforts have paid off in terms of rather well-defined processes, with focus on the structural system (however, thesis has pointed out the building services as a potential area for improvements). Höök (2008) has identified the prevailing culture within the industrialised housing trade as potential obstacle for development. The modularity approach has proved to possess potentials to handle these issues. The challenge is to design interfaces and in order to secure quality, with the embedded possibility for continuous monitoring.

With the companies moving towards a process-oriented production, the performance efficiency becomes essential. In this gap, quality management has the possibility to fill the void. However, the construction trade with its prerequisites of project based production has not paid much attention to this field. With industrialised housing companies and a more process-oriented production, future development may face these challenges. Modularity can thereby be seen as a bridge for the building companies to move towards a quality-oriented production.

In the development and design of the proposed building service modules, there is a possibility to address these issues, i.e. design for production control and value capturing. In the development of quality management, a toolbox of statistical methods has been initiated. For example, Design of Experiments (DOE), that can be used to optimise the performance of a process. There is also Statistical Process Control (SPC), which can be used to monitor the process performance. In the conceptualisation of the proposed modules, key variables should be identified and design should make it possible to monitor these variables in production. All processes possess an inner variance. The challenge is to gain control over this variance (Figure 27).

An unstable process has characteristics where variables are not even assigned to variance distribution. A stable process has known standard deviations, but they are rather large and consequently the process is still subject for improvements. The aim is a robust process, where there still is variance, but the width is narrow and predictable. This variance may be a source for lack of quality. Consequently, it has to be mapped, monitored and if possible reduced. In a process there are different variables, which influence the performance (y). Some of the variables (x) are able to control, while others (z) are influential but difficult to manage (Figure 28).

MODULARITY IN INDUSTRIALISED TIMBER HOUSING
Figure 28. Process model with influential variables x and z, yielding an output y.
REFERENCES


MODULARITY IN INDUSTRIALISED TIMBER HOUSING


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MODULARITY IN INDUSTRIALISED TIMBER HOUSING
Paper I

Lean Modular Design: Value Based Progress in Industrialised Housing

By: Martin Lennartsson, Anders Björnfot and Lars Stehn

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

LEAN MODULAR DESIGN: VALUE-BASED PROGRESS OF INDUSTRIALISED HOUSING

Martin Lennartsson¹, Anders Björnfot², Lars Stehn³

ABSTRACT

One of the core ideas of Lean Construction is that the process of designing and producing a construction product should progress continuously and create value for both the customer and the delivery team.

The hypothesis in this paper is that modularisation has potential as a method for value management. The aim is to describe how modularisation, in a lean context, can be used as a tool to facilitate the management of internal and external values in industrialised housing. The paper will explore the theory of modularisation and its drivers and examine how the method can promote value management.

Modularisation is then explored in practice, using empirical knowledge from the building service systems (HVAC, electricity, etc.) development process at five Swedish multi-storey timber housing producers. The analysis point out the importance of decomposing the modularisation process into a jointly performed industry phase where modules are designed, followed by a company internal product development process that complies to the modules. This paper concludes that it is not the product decomposition into modules that is of importance, rather the process that strives to balance internal and external values.

KEY WORDS

Modular drivers, Industrialised housing, Building service systems, Value management

INTRODUCTION

One of the core ideas of Lean Construction is that the process of designing and producing a construction product should progress continuously, from initial idea to finished product, creating value for both the customer and the delivery team. However, the construction process is often variable due to, e.g., actors with individual agenda, legislations, regulations, influential unions, strong wholesaler networks, etc., making production control difficult, in words of predictability, resulting in wasteful activities (see e.g., Forsberg and Saukkoriipi, 2007).

Lack of control is an issue in traditional site-based construction, which is evident from the continuous use and theoretical development of production

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control methods, such as Last Planner (see e.g., Knapp et al. 2006). Industrialised housing has been developed for many years in Sweden, with the salient idea of moving much of the work from the construction site to factories. By utilizing prefabrication and adding Lean Production practices to their factory based production systems (the entire process, from idea to product), Swedish housing companies are aiming to reduce variation and increase production control.

Ballard (2000) argues that production control intends to create reliable work flow between production units. Logic would thus indicate that production control is gained by thoroughly considering the production units, and the materials flowing through these units. Consequently, as Ballard argues, production control should begin with system design. Swedish industrial multi-storey housing producers are striving in this direction, towards improved production control by utilizing system design.

Björnfot and Stehn (2007a) called this the product offer, a theoretical construct that strives to increase value for both the delivery team (efficiency and profitability) and the customer (flexibility and quality). However, the production culture and business settings of traditional construction still remains, as industrial housing companies balance values from two disparate systems; traditional construction (on-site projects) and manufacturing (factory processes).

Methods, managing and balancing values, are used in construction research and applied practically, e.g., from quality management, TQM or QFD. Internal values for the delivery teams (expectations from stakeholders in design, the way projects are organised and managed in the construction phases, etc.) and external values for the customers (material and equipment quality, design quality and handovers, etc.) must be captured, realised and delivered. According to Kärnä and Junnonen (2005) lean construction (and lean thinking) lacks an adequate conceptualisation of value management, although they point out that Koskela’s third model of production – production is value generation, is near the concept of customer satisfaction.

The hypothesis put in this paper is that modularisation has potential as a method for value management; capture of customer needs (values), transformation into system demands, generation of physical products (transformations) and delivery to the customers. The core in modularisation is the division of a complex product into functional parts that are easier to manage individually than in relation to its whole, i.e. “a module refers to a physical or conceptual grouping of components that share some characteristics” (Jiao et al., 2007). Björnfot and Stehn (2007b) state that it is not the division into modules that is the essence of modularisation. Instead it is the providence of a standardised way of thinking throughout the production process.

The aim of this paper is to describe how modularisation, in a lean context, can be used as a tool to facilitate the management of internal and external values in industrialised housing. This paper begins by exploring the theory of modularisation and its drivers and examines how modularisation can promote the management (capture, generation and delivery) of value. Modularisation is then explored in practice, using empirical data from the building service systems (HVAC, electricity, etc.) development process at five Swedish multi-storey timber housing producers.
A VALUE MANAGEMENT PERSPECTIVE ON MODULARISATION

Ballard and Howell (1998) stated that the general idea of production control is to first stabilise work flow by shielding production against uncertainty. This has to be made before other improvements are possible. However, sources of uncertainty and variety in production are plentiful, e.g., project uncertainty, project complexity, type of contract, production control methods, project typology, space availability on site, risk, technology, tasks interrelationship, decision-making, etc. (Henrich et al. 2006).

Adding to the uncertainty and variation in construction, customers are different entities (persons, companies or organisations) depending on the used perspective, or at what stage in the construction process, work is performed (Björnfot and Sardén 2006). According to Burati et al. (1992) every party in the construction process has three roles: supplier, processor, and customer. Value satisfaction for each of these parties must be fulfilled. As summarised in Björnfot and Sardén (2006), value generation in construction can be classified in two types:

- **External value** is the clients’ value and the value which the project should end up with. External value can be divided into *product value* (the finished building) and *process value* (provides customers with an excellent experience during the construction process).

- **Internal value** is the value created by, and between, the participants (client, contractors, suppliers, etc.) of the delivery team. Internal value strives for an economically efficient production process generating high quality products.

The product offer, viewed from a value management perspective is a well-defined and standardised building system (a product based technical platform) developed from the theoretical principles of lean thinking and the practical value views of specific customers, illustrated in Figure 1. The product offer implies a cultural change in industrialised housing, where value conceptualised into a *product* (house) is central, while keeping the view on production as a critical aspect of value generation.

![Figure 1: Simultaneous consideration of internal and external values in product offer development. Modified from the originally published figure in Björnfot (2006, p.46)](image)

Value management in construction is an on-going research area within the Lean Construction community (e.g., Kämä and Junnonen, 2005; Emmitt et al., 2005). It is in this paper argued that modularisation has characteristics that can facilitate the management of value in construction. In this sense management implies capturing, generating and delivering external and internal value.

3
Bertelsen (2005) argued that the purpose of modularisation in construction is to reduce the complexity of production, i.e., its variability. According to Bertelsen, modularisation has the purpose of reducing production variability by turning the building into a product that can be prefabricated in permanent facilities using established methods and tools for Lean Production.

Modularisation can thus be seen as both a process and a product discipline offering multiple advantages in the whole process. Modularity offers improvements for construction throughout the entire lifecycle of a building, from development to “after-sale” (Björnfot and Stehn, 2004). Consequently, modularisation has potential to improve process control and lower construction variability. However, viewed as a method the scope is much wider, for example Brookes (2005) argues that modularisation in construction helps to:

- Reduce critical points in assembly occurring from 3D-interrelations, i.e. avoid the peril of misfit between component parts.
- Avoid misunderstandings between construction participants (architects, designers, manufacturers and contractors), i.e. reduce risk of ambiguous detailing on drawings, specifications, etc.

The decomposition of a product into *suitable* modules is a more complex undertaking than it may seem. What is a *suitable* module and how are the interfaces to other modules defined? Blackenfelt (2001, pp.8-10) presented a number of module drivers (characteristics that can be used to define and divide a product into *suitable* modular components) and grouped these drivers based on, as Blackenfelt stated: “the three main problems approached by modularity”:

- **Variety versus commonality.** The problem of having a large set of product variants and at the same time standardised production process. Associated drivers are, planned or driven change, upgrade ability, reconfiguration ability etc.
- **Organisation of development and production.** Relates for strategic decisions of how product development and production should be organised and managed. Associated drivers are separate or parallel development processes, in- or outsourcing, use of preassembly, etc.
- **After sale of product.** After sale of product deals with modular decisions concerning the use of products, supervision of products in use and the disposal of products. Associated drivers are ability and need of repair, ability to reuse components and recycling of materials, etc.

From a theoretical viewpoint, modularisation seems to be a method for value management, where internal (production) and external (customer) values are balanced. From a value perspective, modularisation is also a step towards an open building platform (Veenstra et al., 2006) where internal and external values come together.
DEVELOPMENT OF MODULAR INDUSTRIAL SERVICE SYSTEMS

The qualitative and preliminary findings presented in this paper are results from an on-going research and development project. Empirical data is collected from participation at workshops, interviews with industry representatives, observations at production units and construction sites, as well as the study of multiple design and construction documentations (and other literature) detailing the building systems of five Swedish industrialised housing producers (see Table 1).

The participating companies produce a total of 3 500 apartment units annually, which correspond to a share of nearly 20 % on the Swedish market. The incentive for this R&D project originates in the development initiated by the steadily increased use of industrialised timber housing in Sweden.

Table 1: Overview of the five involved housing manufacturers. More information about the structural systems are presented in e.g. Björnfot and Sardén (2006)

<table>
<thead>
<tr>
<th>Company</th>
<th>Turnover (MEUR)</th>
<th>Building system</th>
<th>Product strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>42</td>
<td>Volume building system based on a light timber frame system</td>
<td>Student-dwellings, apartment buildings</td>
</tr>
<tr>
<td>2</td>
<td>42</td>
<td>Volume building system based on a light timber frame system</td>
<td>Apartment buildings, offices, schools and mobile sheds</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>Volume building system based on a light timber frame system</td>
<td>Single family residences, schools, prisons and mobile sheds</td>
</tr>
<tr>
<td>4</td>
<td>18</td>
<td>Volume building system based on massive timber slabs</td>
<td>Student-dwellings, apartment buildings</td>
</tr>
<tr>
<td>5</td>
<td>14</td>
<td>Element structural system (integrates installations and finishing)</td>
<td>Multi-storey residential housing</td>
</tr>
</tbody>
</table>

The industry now begins to coordinate the service systems (HVAC, electricity, etc.) into their industrialised building systems, that is also composed of the production and structural systems.

- **Production system.** The process, which produces the product from initial idea to a finished product (building), thus includes the design and production phases, formed to maximise value and minimise waste (Ballard et al., 2001).

- **Structural system.** The construction platform (volumes, elements, etc.) on which the studied companies base their production systems. See further in, e.g., Björnfot and Stehn (2007).

- **Service systems.** Comprise the necessary services in a building (HVAC and electricity) and the coordination and canalisation of pipes and wires into the production and structural system.
From the perspective of value generation, the current focal point of all industrialised housing companies is to increase internal values, such as production efficiency and profitability. However, much work is still based on traditional construction principles, especially concerning the design, sub-contracting and the purchase of service systems that so far have not seen much adaptation towards an industrial practice. The production process in industrialised housing is based on a fixed, and in many cases, inflexible structural system, which means that the supporting systems such as the service systems have to adapt to the limitations of the production and structural system in the completion of the building (product) (see Figure 2a).

However, alterations in customer values and environmental regulations (leading to demands on energy savings) result in new demands for the housing producers and particularly their service systems. To be able to cope with the current and future development needs, the service systems have to be better coordinated into the building (see Figure 2b). In other words, the services systems should be optimised individually rather than to the existing production system and structural system.

To establish service system limitations and demands, as well as to find a suitable modular division for the service systems, the R&D project runs in two parallel processes; an industry and an academic led process. The task for the industry development process is to facilitate an advance in general knowledge about building and product development of service systems (technical possibilities, limitations and practical use). The goal of the academic research process is to map the current application of building service systems (system possibilities and limitations, as well as potential module drivers), illustrated in Figure 3.

Figure 2: Rethinking industrialised timber housing construction; a) Current state, with superior structural system. b) Desired state, building is superior and value is in focus.

Figure 3: The two processes and the main activities in developing common industrial service systems
THE INDUSTRY DEVELOPMENT PROCESS

To manage the industry development process, a group of senior Swedish construction and technical installation expertise was assigned. They began to work on a roadmap for technical development of the service systems within industrialised housing. The industry development process has three joint objectives:

- **Production system.** Confirm that the production process (and support systems) is designed to maintain the new service systems.
- **Structural system.** Identify critical interfaces between the service and the structural system, and find new technical solutions for these interfaces.
- **Service system.** The main focus; identify new designs and technical solutions for a service system supporting industrialised housing construction.

An open call went out to all Swedish technical consultants, contractors and designers to develop service systems suited for industrial house production. The most prominent ideas (about five to ten) will be further developed into concepts and tried out in actual projects. This process is an ongoing activity.

THE ACADEMIC RESEARCH PROCESS

The first step in the academic research process was to get a firm understanding of the service systems used by the involved companies and the underlying strategy for their developed systems. Therefore an arduous process began of gaining knowledge of the building service systems. The mapping method *Design Structure Matrix* (DSM), used in Björnfot and Stehn (2007b), was utilised to support the mapping of the building service systems. All five companies were studied using this method.

![Design Structure Matrix](image)

**Figure 4:** Excerpt from the DSM modeling of the service systems at Company 4. The matrix is designed to follow the different services, (e.g. heat & ventilation) through out the building system.

Figure 4 illustrates an excerpt from the mapping process of the service systems at *Company 4* (Table 1). The row and column entries represent different parts of the service system. By comparison of the DSM for the companies, common technical solutions (and variances) across different building service systems and company
practices were identified (Figure 4 illustrate how the DSM was used in this analysis.

During this phase in the project, a set of module drivers have also been developed. They have been detected from the DSM analyses, as well as from workshops, interviews and observations at the participating companies.

- **Flexibility to changes in regulations.** Soon a priority will be to address the issues concerning environmental and energy efficiency, as changes in regulations are expected, which will result in altered service systems.
- **Independence from market forces.** Ability to gain control over diversity in products and material, leading to independency from, for example the influence of wholesalers.
- **Ability for external product development.** Possibility to develop modules individually so they can be outsourced (Lau and Yam 2005). The producer then has the choice to focus on the core processes.

**DESIGNING FOR MODULARITY IN INDUSTRIALISED CONSTRUCTION**

The qualitative based results in the R&D project show that external value (to offer more and improved values for the customer) becomes more important in the product offer development. This is a shift from the single company’s focus on product offer development to a situation where the companies are willing to collaborate in order to achieve a common platform for the service systems. The management of external values has become so important, that the housing companies are ready to break the restraining impact of their rigid production systems to a situation, where individual modules are more important, as illustrated in Figure 2b. Also evident from the R&D process is that the companies are confident in modularisation as the working method to reach the goal of an improved industrialisation process.

The most important challenge of a modularisation initiative in industrialised housing becomes the undertaking of a common industrial development, performed as a joint venture. In other words, the establishment of standards across the industry in order to improve production control (reduce variation in used resources).

In the modularisation process, it is central that the structural and production system of the companies become subordinate to the modular division. Consequently, it is important to divide the modularisation process into a joint industry development phase, followed by a company internal product development. In the second phase the generic modular system is adapted and fitted into a specific structural system and concurrently into the production systems. The employed strategy is illustrated in Figure 5. The management through modularisation yields a value generation not solely based on internal values but also on external customer values (a systems view on value).
DISCUSSION AND CONCLUSION

In this paper, a modularisation initiative was advocated to be a method that can unite the construction industry towards common interests; i.e. reducing variation in order to gain control and obtain increased predictability. As a consequence, process efficiency and quality will improve. This paper argues that it is not the commission to actually divide the product into modules that is important, rather it is the process of modularisation that strives to balance internal and external values.

Common applications of modularity usually start with transferring customer needs into product demands, using for example QFD. This paper indicates that to take advantage of modularity, at least initially, a generic standardised construction platform is required; following this, individual companies can build independent and robust product platforms.

Why is the industrialised housing industry in need of modularisation? In their advance, the companies have encountered barriers to their expansion, which in all likelihood is related to the culture of traditional construction (Höök and Stehn, 2008). Two examples of progress obstacles specifically concerning technical installations are the influence of unions (leading to competition and individualism, instead of unification and shared goals) and the wholesaler market with a large material and product diversity leading to high costs, instead of standardisation that will result in cost reduction for the companies.

It is assumed that the traditional construction culture is the largest obstacle to the acceptance of industrialised housing construction. Evidential proofs from the on-going R&D project indicate that single actors within the construction industry are not able to carry the development forward. The companies have realised that they must cooperate in order to take charge of the process and change the culture towards an environment with industrial practice in house manufacturing.

In connection with a modularisation initiative, issues concerning manufacturability can emerge (Jiao et al., 2007). This is part of the problem with variety versus commonality (Blackenfelt, 2001). In lean construction this problem is related to work structuring. Tsao et al. (2004) state that work structuring includes concerns of how operation and process design align to product design, supply chain structure, allocation of resources and design for assembly. An incentive from properly defined modules is outsourcing (ability to develop modules individually) and also improved production control. In this regard work
structuring might be interesting to investigate further as the R&D process progresses.

The authors emphasise that the project is at an initial stage, where actual modules have not yet been developed. However, the conviction is that the modularisation strategy is sustainable, proved by the fact that five competitors concur to cooperate and develop a common platform that can work as a foundation not only to themselves but also to other actors in housing construction.

ACKNOWLEDGEMENTS

The research in this paper has been funded by two centres for research and development, TräCentrum Norr and Lean Wood Engineering. The authors would also like to acknowledge the companies and their representatives for participating in the project and providing data and experience to the study. Finally the authors would like to express gratitude to Ångpanneföreningens forskningsstiftelse for their contribution, making it possible to attend IGLC-16 and present the findings from this research.

REFERENCES


Production Control through Modularisation

By: Martin Lennartsson, Anders Björnfot and Lars Stehn

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

PRODUCTION CONTROL THROUGH MODULARISATION

Martin Lennartsson 1, Anders Björnfot 2, Lars Stehn 3

In Sweden, the industrial housing trade has developed for many years with the salient idea of improving production control through an increased level of prefabrication. However, production variability is a consistent issue as work is still sub-optimised, resulting in a fragmented production process. Consequently, problems arise when prefabricated parts and components are assembled. The building services are often a source of high variability (many different components and subcontractors), leading to reduced production control. The aim of this paper is to present how modularisations can provide prerequisites for production control in service system design.

So far, modularisation has only rendered little attention in Lean construction. In this paper, a modularisation development effort of five Swedish industrial housing companies is reported. To generate a relevant set of modules, several workshops were held together with company representatives and building service consultants. The Design Structure Matrix (DSM) was used to detect the lowest common geometrical denominator of the building service systems as well as crucial connection points and interfaces. Combining the DSM with qualitative module drivers generates a design for service system modules facilitating improved production control.

KEY WORDS
Production Control, Building Services, Modularisation, Module drivers.

INTRODUCTION
An important theme within the Lean Construction community is production control. The general idea of production control is to protect against uncertainty in production (variation in production tasks, deliveries, etc.) (Ballard and Howell, 1998). Production control, in Lean Construction terms, is generally said to be gained by creating reliable work flows between production units and therefore production control should begin with defining the building at an overall level (customers, components, organisation, etc.). Henrich et al (2006) presented an overview of production control within the construction trade, concluding that the strategy depends on context and setting.
Consequently, the issue to gain production control has been addressed in a number of ways, e.g., in relation to Lean Construction, using tools such as Kanban, Critical Chain and of course the Last Planner system. These tools mainly concern the planning and production phases of construction and therefore actively attempt to achieve control by improved management and production planning activities. Lean methods or tools that proactively strive to create prerequisites for production control in earlier stages of the construction process are less common in construction literature.

According to Morris and Donnelly (2006), modularisation is a method/tool that contributes to achieve consistent quality and allow firms to provide a wide range of up-to-date products at affordable prices. For off-site construction, Lennartsson et al (2008) suggested that modularisation is useful in capturing and balancing internal and external values. Modularisation thus seems to have a proactive aim in reducing and better controlling variance (in material and information flows) that can occur during production. In prefabrication, customer values must be declared early. Therefore, any change in design can cause variation leading to production delays; e.g. to gain better control of production. Veenstra et al (2006) emphasised the significance of creating modules for the complex and arduous service system (HVAC, electricity, etc.) work.

The aim of this paper is to describe how modularisation can be applied as means to create prerequisites for production control. This paper first provides an overview to the field of production control within lean construction. Then modularisation theory is explored in the sense of how production control can be managed. Finally, a logical chain of empirical studies was conducted in relation to a practical modularisation process within Swedish industrialised housing, aiming to develop modules for building service systems. The goal of the studies was to validate a selection of module drivers proposed for creating prerequisites for production control.

PRODUCTION CONTROL – A GENERAL OVERVIEW

Production is the act to make products (goods and services) while control is used in a variety of contexts to express “mastery” or “proficiency”. Thus production control is about gaining mastery over the production process. Production planning and control is a mature research field (Stevenson et al 2005) and the issue to achieve production control in construction is therefore not new. For example, Ballard and Howell (1998) stated that production control is about shielding production from uncertainty, while Henrich et al (2005) reviewed existing production control methods in construction.

van der Bij and van Ekert (1999) stated that “the production control system comprises a system of tasks, methods, and means, which an organisation uses to agree and maintain the availability of products to the expectations of the internal or external customer with respect to time, quantity, and place”. Production control in manufacturing can be achieved through (Stevenson et al 2005), e.g., Kanban, Manufacturing resource planning (MRP), Theory of constraints (TOC), Workload control (WLC), and Constant Work In Process (CONWIP). For construction, one of the most recognized and applied production control tools is the Last Planner system™.
Other used tools to gain production control in construction are e.g., Critical Path Method (CPM), Critical chain (CC), Line-of-Balance (LoB) and Kanban. Common for these tools is that they are developed to function in on-site project environments. Additional tools capable of addressing production control in early stages of construction (essential in the case of prefabrication) are Poka-Yoke (PY) and Set-based design (SBD). SBD can be applied in early phases of construction to proactively achieve production control through an improved design process, i.e., the design process is controlled so it facilitates a streamlined production process, minimizing waste. In Figure 1, the methods mentioned above are related to each other and to the construction process phases of design, manufacturing and production.

As illustrated in Figure 1, there seems to be a lack of production control methods or systems that can be applied early in prefabrication to provide proactive control of production events. This paper proposes that modularisation can play such a role in the design phase. However, it is important to emphasize that modularisation does not have the goal to actively control production. Rather, modularisation should be seen as a facilitator of production management, since expected variances can be controlled.

**PRODUCTION CONTROL THROUGH MODULARISATION**

Modularity (or modular design) is an approach that subdivides a system into smaller tangible entities (modules) that can be independently created and used in different systems to drive multiple functions (Voordijk et al, 2006). Modularisation is the undertaking to design a modular system. Most modularisation initiatives in construction are found within this area. However, in prefabrication, modularisation is argued as means to create standardised parts, produced in optimised processes, i.e. the essence of modularisation is not modular division, rather a standardised way of thinking all through the process (Lennartsson et al 2008).

Bertelsen (2005) stated that the purpose of modularisation is to reduce production variability by turning the building into a product that can be prefabricated in permanent facilities using established Lean methods and tools. Erixon et al. (1996) refer to this as ‘products in products’ and ‘factories in the
factory’. For example, Court et al (2008) report on modular initiatives within Lean Construction reducing variation and minimizing waste in assembly, while Brookes (2005) noted that tangible components are easier to coordinate and misfits can be avoided.

As was argued in Lennartsson et al (2008), a successful modularisation effort will capture and define customer values (both internal and external) implying that variations within the supply chain can be better controlled (Voordijk et al, 2006). Using modular products, it is, possible to design a production process that provides a wider range of variants depending on what the customer demands (Morris and Donnelly, 2006), i.e., increased product variety with reduced process variation.

It seems, modularisation can provide production control from many perspectives. Voordijk et al (2006) discuss modularisation as a three-dimensional concept concurrently considering the product, the process and the supply chain. It can be argued that modularisation strives for production control in these three areas through:

- **Product modularity** specifies the product so that materials, components and other resources required for production is known and can be controlled, i.e. degree of component independence and interface standardisation. For example; if ten different connected components each have 5% risk of erroneous tolerances, then there is 40% risk of failures in assembly.

- **Process modularity** refers to management of production, establishing and controlling production methods, i.e. how the product is made. The industrialised housing trade is aiming for high degree of prefabrication, which demands a higher degree of planning and preparation than on-site building.

- **Supply chain modularity** refers to who does what, i.e. decides participants involved so responsibilities and delivery requirements are known and can be controlled and monitored. For example; if each supplier to an assembler have a delivery accuracy of 90%, then there is a 10% risk of at least one component missing during assembly if not relevant buffers are set.

According to Erixon et al (1996) the first step in a modularisation process is to specify the product using Quality Function Deployment (QFD). Then technical solutions are selected in respect to manufacturing goals. In the third step, modular concepts are generated with aid of module drivers (Table 1), defining reasons to perform a modular division and works as a link between module requirements and the production system.
Table 1: Overview of the generic module drivers presented by Erixon et al. (1996)

<table>
<thead>
<tr>
<th>Generic Module Drivers</th>
<th>Drivers (A-L)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A</strong> Carry over. Solutions can be carried over to new product generations.</td>
<td>G Process/Organisation. Special know-how, pedagogical assembly, lead times.</td>
</tr>
<tr>
<td><strong>B</strong> Technology evolution. Guard for technology shifts during product cycle</td>
<td>H Separate Testing. When functions can be separately tested.</td>
</tr>
<tr>
<td><strong>C</strong> Planned design changes. Controlled by customer demands.</td>
<td>I Purchasing. Delivery as a “black box” to reduce logistic costs.</td>
</tr>
<tr>
<td><strong>D</strong> Technical specification. Concentration of variant changes.</td>
<td>J Service and maintenance. Ease of management as separate modules</td>
</tr>
<tr>
<td><strong>E</strong> Styling. Influences from trends and fashion.</td>
<td>K Upgrading. If upgrades are expected.</td>
</tr>
<tr>
<td><strong>F</strong> Common unit. Sub-function with similar physical solutions.</td>
<td>L Recycling. Concentration of recyclable material to one module.</td>
</tr>
</tbody>
</table>

The fourth step in the modularisation process evaluates concepts and tests interfaces. The interfaces are a key consideration as they influence the characteristics and flexibility of the final product. The fifth and final step concerns the improvement of the specified modules in respect to assembly strategies. Modular division through module drivers has been applied in practice in various environments in manufacturing. In construction, Veenstra et al. (2006) put forward a driver regarding a variable to capture the risk or need for components to change over time.

Considering all of the presented module drivers is an arduous process since they are so numerous and also hard to fit to construction, e.g. in construction, carry over is rarely spoken about. However, considering the three distinct areas (product, process and supply chain) that above was argued to provide production control, three of the module drivers emerge as influential in facilitating production control:

- **(F) Common Unit.** As industrial builders depend on the whole construction trade to accept their prefabricated components, it is necessary for all participants to adapt to these components. Therefore, it is important to find functions present in several product variants and provide them with the same design. Variants in demand can then be produced with fewer components.

- **(G) Process/Organisation.** Modular products manufactured in main and supportive processes, facilitate a production system that will help lower lead times and improve quality. Cultural issues in prefabrication lead to strained supplier relations as contractors and housing manufacturers have short term relations with subcontractors and suppliers (Höök and Stehn, 2008).

- **(I) Purchasing.** It is important to gain control of material and components in order to lower wholesaler influence. Properly defined modules allow material deliveries in “black boxes”, lowering costs for logistics and providing more power for the companies in price negotiations.
CASE STUDY: BUILDING SERVICES IN INDUSTRIALISED HOUSING

Five small to medium sized Swedish industrial housing companies (Table 2) have agreed to cooperate in order to facilitate design and management of building services (Lennartsson et al. 2008). The companies base their production on a high degree of prefabrication (> 80 % work in off-site production facilities) considering modula-risation as a feasible method to find product solutions that appeal all participating companies; the building service modules should fit the different production systems.

Table 2: Overview of the five involved housing manufacturers.

<table>
<thead>
<tr>
<th>Company</th>
<th>Turnover (MEUR)</th>
<th>Building system</th>
<th>Product strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>42</td>
<td>Volumetric units</td>
<td>Student-dwellings, apartments</td>
</tr>
<tr>
<td>2</td>
<td>42</td>
<td>Volumetric units</td>
<td>Apartment buildings, offices</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>Volumetric units</td>
<td>Single family residences, schools</td>
</tr>
<tr>
<td>4</td>
<td>18</td>
<td>Volumetric units</td>
<td>Student-dwellings, apartments</td>
</tr>
<tr>
<td>5</td>
<td>14</td>
<td>Element structural</td>
<td>Multi-storey residential housing</td>
</tr>
</tbody>
</table>

Early in the project, three studies (Figure 3) were conducted to gain understanding of building services issues. Market Exploration proved that wholesalers control the market with a catalogue of more than 100,000 articles. The study suggested a plug-and-play system as a viable path of development. In Map Electric, the current process was mapped to spot improvement. In Plug & Play, was decided to test the feasibility of a plug-and-play system. The evaluation highlighted a resistance to change at building services subcontractors, who emphasised problems and obstacles rather than advantages. This supported the idea of a joint industry venture for modularisation.

Together with the case companies, it was decided to perform a Competition to explore new innovative building services. An open call went out to all consultants, contractors and designers in Sweden with the task to develop service system solutions suited for industrialised housing. The thorough inquiry included specification of the current production systems (Overall Mapping) and specified necessary characteristics and technical solutions, e.g. a prefabrication level of 80 %. However, all proposals lacked a systems view since not all required service systems were included. After the competition, solutions were discussed to identify implementation possibilities. Results (product, process, and supply chain) from the studies are presented below.

Figure 3: Empirical studies conducted to validate proposed module drivers.
SERVICE SYSTEMS – THE PRODUCT

A Design Structure Matrix (DSM) was used to map the building services in a generic building (Figure 4) valid to all case companies. Seven types of media must be provided for each apartment; Heating [1], Hot [2] and Cold [3] water, Drainage [4], Ventilation [5], Weak Current (TV/Telecom/Computer [6]) and Power Supply [7].

The different systems distribute media to the user units within the building. These are closed systems consisting of ducts, pipes and wires. The categories of the DSM (Figure 4) represent different spaces within the building where building services are present and required. Reading the DSM row-wise shows media going out of an entity while reading the DSM column-wise reveals media coming from another entity. For example, services enter a building through an external feed (A), travel through the Central Feed Unit (B) into the Basement (C), through vertical shafts (E) to horizontal feeds in Traffic Volumes (G) and then to living quarters inside volumes (H).

As many service system components as possible are assembled at production facilities; wires and sockets are installed in walls and roofs, while pipes are placed in floor elements. In addition, interior slots are assembled to hold ventilation ducts. Excluded from off-site work is canalisation (shafts) to reach higher floors, and to connect shafts to volumetric units. These couplings are made on the construction site.

SERVICE SYSTEMS – THE PROCESS

The production process is divided into two parts; in the factory, wires and pipes are assembled into floors and walls. Then the panels are assembled to volumetric units, wires and pipes are connected, and sockets installed. In the second phase installations are completed on-site. The power supply production process was documented using a stop-watch and video-recorder. This study highlighted the many different activities taking place in building service assembly resulting in high lead times as the risk of errors grow with increasing activities and relations (between physical components and subcontractors). Table 3 displays an excerpt from the mapping study illustrating five common assembly errors and an...
estimation of needed correction time (estimation by the subcontractors). The assembly activities have a cycle time of five minutes or less.

Table 3: Errors and correction times (1 unit = 5 minutes) for subcontractors in power supply assembly. Boxes are sockets and switches for electrical assembly while duct holes are used for ventilation ducts.

<table>
<thead>
<tr>
<th>#</th>
<th>Type of error</th>
<th>Elec.</th>
<th>HVAC</th>
<th>Carpet</th>
<th>Paint</th>
<th>Carpenter</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Box misplaced in ceiling</td>
<td>12</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td>18</td>
</tr>
<tr>
<td>2</td>
<td>Box behind kitchen inter.</td>
<td>12</td>
<td>4</td>
<td>12</td>
<td></td>
<td></td>
<td>28</td>
</tr>
<tr>
<td>3</td>
<td>Box behind tiles in bathroom</td>
<td>12</td>
<td>24</td>
<td>12</td>
<td></td>
<td></td>
<td>48</td>
</tr>
<tr>
<td>4</td>
<td>Radiator pipes misplaced in floor</td>
<td>24</td>
<td>12</td>
<td>12</td>
<td></td>
<td></td>
<td>48</td>
</tr>
<tr>
<td>5</td>
<td>Duct holes misplaced in slots</td>
<td>18</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>18</td>
</tr>
</tbody>
</table>

Correctional time is derived from additional activities carried out by the subcontractors, e.g. misplaced boxes require a new installation and correction of the erroneous placement. Errors can be traced to incorrect drawings, as they are passed on between designers and subcontractors without validation. Errors lead to increased production times with up to 48 times (Table 3), not including delays of other activities that can obstruct assembly of correct units. This leads to an increase in overall lead times that cannot be predicted (a challenge to any production control system).

SERVICE SYSTEMS – THE SUPPLY CHAIN

Figure 5 displays the supply chain for one of the case companies in factory production. Dotted parties represent external resources, while the remaining parties are “owned” by the company. As displayed in the figure, several actors are involved in the building services that are not in-house personnel and the arrows show the many different ways information and materials are transferred between participants. Figure 5 should at this stage only be viewed as an example of the complexity in relations.

Information and material flows must be considered in terms of securing delivery of drawings and materials on agreed times. Different designers are independent and don’t have regular contact with each other. The fact that designers and subcontractors are procured on short-term contracts on a project to project basis pose additional problems in relations, i.e. drawings are distributed to factory personnel and procured subcontractors without synchronisation or validation, and if necessary materials are provided by subcontractors, they will charge for full material coverage.
Evaluation of the plug and play system proved possible cuts in lead times up to four times. Moreover, the results showed the need for a better coordinated supply chain as wrong components were delivered, and agreed-on delivery times were exceeded. One reason was poor design made in a hurry. There is also ambiguity in the regulations when it comes to the demand for inspections in the joints where the plug and play system is to be connected. Commonly, the regulations are interpreted in such a way that these joints cannot be built behind the plaster boards in the walls, which was why it was decided to keep the joints unveiled in this case. Additionally, the subcontractor opposed this kind of system, as the current situation provides power to the building service trade where subcontractors can charge maximum work hours.

**DESIGN OF A MODULAR SERVICE SYSTEM**

The DSM detected suitable interfaces for modular division. The analysis shows that vertical **Shafts (E)**, **Traffic Volumes (G)** and the basement holds all seven media types. **The Shaft (E)** is, in a way, already a module with set boundaries, but all assembly is performed on-site which causes interferences and delays. There is a need to coordinate the media flowing in the shaft, e.g. separate media that affect each other such as hot and cold water. Development of a prefabricated shaft module is proposed. The **Traffic Volume (G)** and the **Basement (C)** both have horizontal canalisation of media, with similar opportunities to create a prefabricated inner ceiling module.

**PRODUCTION CONTROL THROUGH COMMON UNITS**

The module driver common unit manages a frequent problem in assembly of building service, pipe dimension errors. Often pipes with diameters of both 15 and 16 mm are used that can be accidentally mixed increasing risk for leakage, i.e. it is difficult to secure a tight joint between two pipes of different dimensions. A reason is the use of components from different brands. Instead, specifying a narrow set of discrete dimensions for pipes (e.g. 15, 18, 21 mm) only allows for correct jointing lowering the risk of faulty assembly. Further, the problem relates to how subcontractors are procured; as subcontractors normally work in different projects at the same time for different contractors using own materials, thus mixing of components is unavoidable.
**PRODUCTION CONTROL THROUGH PROCESS/ORGANISATION**

Process/Organisation relates to how and where value adding activities will be performed. High levels of on-site assembly require much on-site coordination (e.g. on-site work structuring of subcontractors), while a large degree of prefabrication demands better planning in design, e.g. assembly errors from poor design can be costly due to the level of standardisation. The case companies are focused on the latter view. In order to gain production control with respect to process and organisation it is desired that shafts and ceilings are manufactured parallel to the main process with a specified and minimised set of materials and required activities in order to reduce interface, mismatches, e.g. piping dimensions, faulty drawings, etc.

**PRODUCTION CONTROL THROUGH PURCHASING**

Purchasing can facilitate production control by further narrowing allowed materials used, e.g. pipe dimensions. Material purchase can then be made in respect to the needs and boundaries of the modules by specifying standardised bill of materials that lower inventories and waste while improving material forecasting. As a consequence, the purchasing division can focus on procurement of fewer components, as previously mentioned. Control of required materials prohibit subcontractor to make the purchase in order to lower costs and avoid risk of mixing materials from different brands.

**DISCUSSION AND CONCLUSIONS**

In this paper, the main incentive put forward for a modularisation initiative is to provide prerequisites for production control. With this means that modularisation is applied early in the construction process at the product level to proactively reduce variation during production and in the supply chain. The case study results highlight the importance of interfaces in products, processes and within supply chains for production control. An example of a product interface is the high risk of errors in piping connections, while unconfirmed drawings passed on to subcontractors is an example of a poor process interface and also show evidence of fragmented supply chain interfaces as subcontractors are often procured on a project to project basis.

Prerequisites for production control are achieved in practice through three module drivers (common unit, process/organisation and purchasing), in this case resulting in development of shaft and inner ceiling modules for building services. The proposed module drivers are interrelated as specification of a narrow set of components affect purchasing in respect to how supply of materials is secured. Further, modules work in collaboration with Poka-Yoke as module interfaces, by design, shield from erroneous assembly through standardized pipe dimensions and interfaces, thereby improving production control. These results are in line with those presented by Fine et al (2005) who state that modular products tend to have modular processes and supply chains.

Hofman et al (2009) noted that suppliers tend to be reluctant to adopt new standards. Similar results were obtained in the evaluation of the plug-and-play system where the electricians emphasised the problems rather than lifting up the
advantages and possibilities. The case study findings are also in line with Halman et al (2008) who stated that modularisation initiatives within construction need to address issues with restrictive regulations, which lead to the ambiguity in interpretation of regulations as was highlighted in the evaluation of the plug and play system.

Modularisation has possibilities of becoming a potent tool in the design phase in order to facilitate other production control methods within the construction industry. Production control can be further facilitated through better adaptation of the product into the production process, i.e., opportunities to apply the Line-of-Balance technique as well as coordination and monitoring on-site with support from Last Planner.

ACKNOWLEDGEMENTS

The authors thank the participating companies and the research centres of TräCentrum Norr and Lean Wood Engineering, as well as the research foundation of Åke och Greta Lissheds Stiftelse for funding the research.

REFERENCES


Appendix 1: Consultant Procurement Questionnaire
Appendix 2: Production process activities for electricity
Appendix 3: Assembly time for electricity in two volumetric units
Appendix 1: Consultant Procurement Questionnaire

Functionality
- What kind of systems can you work with?
- Does the proposal fulfill demands from clients, customers, regulations etc.?
- Can adaptations be made with respect to altered and new demands?

Ability to for commonality and adaptation
- Does the proposal allow upgrading?
- Is the proposal adapted to be implemented in a generic building system?
- What are the possibilities to make add-ons beyond mandatory systems?
- The demands on energy efficiency will be tighten up in the near future, what is your opinion on the additional efforts that will be needed?

Costs
- What are the economical advantages of your proposal?
- What is the savings potential if functionality should be kept intact?
- What investments are demanded to implement the proposal?
- Do you think your proposal relies on previous experience or is it new and untested?
- Does the proposal need educative efforts?

Tolerances
- How should control be gained over tolerance demands in the emerging interfaces?
- What measurable parameters have you identified as crucial to secure the quality?

Manufacturability
- What is demanded technically in the production to realise the proposal?
- Can manufacture be isolated in relation to the other production?
- What advantages are achieved concerning maintainability and administration?
- What will the proposal impose from a purchase division point of view – Will the number of components be manageable, also for the individual companies?

Organisation
- What demands are put on organisation in your proposal?
- What are the advantages from your proposal by integration with other design functions?
- Can you make an estimate on the needed work time?
- Will demands be put on the production in respect to authorisation and special skills?
Appendix 2: Production process activities for electricity

In detail the different activities in the walls can be described as follows:
- Plaster boards piercing to prepare for box assembly.
- Box assembly in frame.
- Box assembly in noggin piece.
- Piping to and between boxes going through frames.

And in the ceiling:
- Plaster boards piercing to prepare for box assembly.
- Box assembly.
- Pipe assembly.

<table>
<thead>
<tr>
<th>#</th>
<th>Activity</th>
<th>Element</th>
<th>Assembler</th>
<th>Time (min)</th>
<th>+/-</th>
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<td>Piercing for one box</td>
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<td>2</td>
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<td>Piercing for hatch (stove, central etc.)</td>
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<td>Carpenter</td>
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<td>6</td>
<td>Assemble box &amp; noggin piece</td>
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<td>7</td>
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Appendix 3: Assembly time for electricity in two volumetric units

The different activities refer to the categorisation in the activity list presented in Appendix 2. Then the total number of activities is summarised.

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