Product Quality through Experience Feedback in Industrialised Housing

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PRODUCT QUALITY THROUGH
EXPERIENCE FEEDBACK
IN
INDUSTRIALISED HOUSING

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"The solutions all are simple - after you have arrived at them. But they're simple only when you know already what they are."

(Robert M. Pirsig)
PREFACE

This thesis summarises a working period of almost three years. I have enjoyed every moment good and bad. It has been and still is a period of personal and academic development. I now know that my knowledge is infinitely small and that it is my responsibility to seek improvement. There are of course a lot of people that have helped me to reach this level of understanding, and I would like to express my profound gratitude to:

- My supervisor Dr Helena Johnsson for guiding me in the academic universe and for valuable scholarly scientific mentorship as well as personal support in my struggle to believe in the process of becoming a researcher,
- Professor Lars Stehn for an inspiring attitude, and for providing a working arena characterised by an atmosphere of trust and common strive at the department,
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- I want to express my gratitude towards Tarja Tervonen and Monica Björnfot for enduring efforts to guide me in the practical administration of my life as a PhD student at Luleå University of Technology; without you I would drift off and get lost in the space of academic administration.

I would also like to emphasise the part of life making it all worthwhile:

My beloved daughter Sara for always grasping a new day with lively curiosity and energy. Helena, the mother of Sara, for keeping a quality level regarding parental responsibilities. Olov and Johan for sharing your mother with me. Finally, my greatest love Lisa, for sharing the every day life, filled with love, respect and patience, accepting my love and always inviting me to bring out the best.

Luleå, October 2008

John Meiling
ABSTRACT

This thesis is based on six chapters and four appended papers. The work has been conducted with a focus on product quality and feedback. Hypothetically, industrialised housing gives better product quality and improved control in production. Industrialised house builders work with the prefabrication of building parts for later assembly at the building site. Timber framed volume production represents one form of industrialised housing. These house builders strive to control their products as they develop from conventional building firms into industries where quality management is a major concern. This effort becomes evident, e.g., in supply chain relations, which are long-term and well-defined in industrialised housing. The overall aim of this thesis is to investigate product quality through experience feedback at an aggregated product level in industrialised construction. It is suggested that houses be viewed as products instead of projects, based on the understanding and view of how industrialised housing can benefit from Lean and quality management theories.

Quantitative and qualitative data concerning wooden stairs and timber framed volume production were collected. Results are based on data gathered through a single and a multiple case study. The single case study presented in paper I include a complementary study, three focus group meetings and a series of interview. A questionnaire was distributed to 700 tenants at 13 different habitats. One multiple case study employing four timber framed volume producers was presented in papers II-IV. Results are based on data gathered through semi-structured interviews, and statistical analysis of quality audits from three phases in the building process was studied. Defects from quality audits were coded, sorted and analysed regarding origin, cause and action required for correction.

The single case study shows that efforts are being made to develop new industrialised housing products, though a lack of appropriate management structures hinders the quality assurance of product development. The study also reveals a shortage of available data to execute Service Life Planning. Results from the multiple case study reveal a company focus to streamline the production process, even though experience feedback between departments at the company was minor or absent. Organisations within the companies offer the possibility for experience feedback, which is not currently functioning. In addition, 21 % of all recorded defects can be directly linked to the structural design phase, building system or both.

Based on the aim and by exploring the theoretical framework of quality management, service-life planning and Lean theories, it is concluded that industrialised house builders refrain from using established quality frameworks to improve their product and that product quality is currently the same as elsewhere in construction. However, the possibility to implement product quality management is large, since the prerequisites for success are present, namely production control, ownership of the building process and established supply chain relations. Feedback is not functioning due to a lack of decision of overall improvement and no allocated resources for product development and quality engineering. So far, the transformation of collected information is non-existent.
SAMMANFATTNING


Den första fallstudien visar att husbyggnadsföretagets ledning inte har prioriterat produktutveckling. Vilket medför att nödvändiga data för utförandet av livslängdsplanering inte finns tillgänglig. Detta beror på att erfarenhetsdata inte har någon naturlig organisatorisk hemvist på företaget. Den multipla fallstudien visar att företagen lägger ner arbete på att effektivisera fabriksstörverkningen men att erfarenhetsåterföring mellan avdelningarna inte fungerar, även om organisationen egentligen är väl anpassad att ingripa erfarenhetsåterföring. Att ta vara på tidigare erfarenheter är av stor vikt vid industriell tillverkning, vilket visar sig i undersökningen, då 21 % av de undersökta felet härstammar från projektieringskedet och från byggsystemet.

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1 INTRODUCTION

This chapter sets the background to the research area and discusses the proposed problems regarding quality and feedback in construction. The aim and research questions are presented and the demarcations are stated. Finally, the structure of the thesis is outlined.

1.1 Background and problem description

Investments in housing production were 220 billion SEK in 2006, employing 11% of the total national work force, and constituting 8% of gross national product (SBI, 2007). Its products are expected to last 50-100 years. Even small enhancements in cost and life cycle performance will affect the national economy as well as the economies of clients and consumers. Building construction generally involves large amounts of waste, and often poor relationships between various parties with conflicting interests that tend to affect both quality and profit (SOU, 2002). Josephson and Saukkoriipi (2007) conducted an extensive inventory among Swedish building projects, stating that the amount of waste is 35% of the total production cost. Of the total project cost, the cost of defects alone are stated by Saukkoriipi and Josephson (2006) as 5% and the cost for rework is stated by Love and Edwards (2005) as 6.4%. The waste statement corresponds to non trade-specific studies of poor quality costing, which state the potential to be in the range of 30% (Sörqvist, 1998). Josephson (1994) states that waste can be reduced by learning, concluding that the hindrances for knowledge transfer in construction are fragmented organisation and production process, as well as the notion that learning is difficult within construction itself. This leads to an interest to investigate information feedback and how it can support enhanced quality in construction.

Quality is complex and multifaceted, which in turn leads to problems when communicating it as a concept (Garvin, 1984). In the manufacturing industry quality has become an important and obvious means of lowering poor quality costs, competing for market shares and improved profitability through standardisation, customer focus, and continuous improvements through experience feedback (Bergman and Klefsjö, 2003). This development originates from product quality theories that have developed since 1948, with Japanese engineers benchmarking their American colleagues who worked with quality control at Bell Laboratories (Deming, 1986).

The development is referred to as the quality story (Dahlgaard and Dahlgaard-Park, 2006), and has today developed into what is referred to as the third generation of quality management (Foster and Jonker, 2003). In a simplified manner, the generations are: (1st) product quality control (2nd) Total Quality Management and (3rd) stakeholder oriented (ibid). Incentives for the construction sector to reuse information and learn from experience are well documented, e.g (Landin, 2000) and (Persson, 2006). Instead of working according to quality management principles, the construction hero is a person who quietly solves all production problems in different ways. An increasing demand from authorities and clients for quality assurance has led to initiatives to also implement quality management at construction companies (Landin, 2000). However, product quality through feedback and the reuse of experiences is considered a fundamental basis for successful production of any manufactured product, though it is said to be generally difficult in construction (Josephson and Saukkoriipi, 2007, Landin, 2000, Sigfrid, 2007). If concern for product quality is the first step in quality management, the entrance to a company-wide approach to quality, i.e. Total Quality Management (TQM), is claimed to be the ISO 9000 standards (Poksinska, 2006, Bergman and Klefsjö, 2003, Dale, 1999). Since 1995, authorities in Sweden require that construction companies have a certain knowledge of ISO 9001 (BFS, 1996). An action of quality is thus to implement quality systems that are structured according to ISO 9000, but quality management often fails when the reason to adopt quality management principles and routines comes from a desire to not lose customers (Dale, 1999, Gustafsson et al., 2001, Poksinska, 2006). Low and Peh (1996) suggest a
framework for implementing a TQM quality system in construction. Low and Teo (2004) later state that the success of TQM has yet to be proven in construction, as Total Quality Management and quality assurance are derived from the automotive industry.

Another quality and production improvement theory developed from the automotive industry is the Lean production concept (Womack et al., 2007). The Lean production concept later developed into Lean construction (Koskela, 1992). The International Group for Lean Construction (IGLC) was founded in 1993 and have since then aimed at contributing in the enhancement of the construction industry (IGLC, 1993). The IGLC vision is stated as follows:

*Our goal is to better meet customer demands and dramatically improve architecture, engineering, and construction process as well as product. To achieve this, we are developing new principles and methods for product development and production management specifically tailored to architecture, engineering, and construction industry, but akin to those defining Lean production that proved to be so successful in manufacturing (IGLC, 1993).*

Lean construction is adapted from Lean production and the Toyota production system. Koskela (2000) states that production in construction should be performed using transformations of inputs into outputs, where material flows through value and non-value adding activities with value for the customer as the end goal. Lean construction is concerned with the efficiency more than effectiveness of construction projects and implement tools and methods for mainly site production projects (Björnfot, 2006). Ballard (2000) describes the importance of systematically identifying deviations and how control can be maintained through continuous actions.

The concern for enhanced product quality and balanced product life length in construction is formalised in the ISO standard for Service Life Planning ISO 15686. Building or constructed assets should respond to customer and authority requirements at a reasonable cost for the planned service life (Jernberg, 2005). Emphasis of Service Life Planning as an effort to ensure building performance dates back to the formation of the European community initiative: Construction Product Directive (CPD) in 1988. Service Life Planning is identified as a guiding concept regarding the durability of buildings (Sjöström et al., 2002), which should help in implementing CPD. Service life per se is not the durability of one material, but a more holistic approach to buildings as a complicated system of components and materials. The Service Life Planning standard presents a structure to utilise performance-based requirements and to implement routines for the comparison of design alternatives in construction. However, because the building sector develops most products with reference to standards and not requirements, there is no linkage between requirements and product design as of yet (Trinius and Sjöström, 2005). Decisions concerning the choice of material, components and installations that affect the durability of the buildings, as well as the operating and maintenance costs during their service lives are taken during the design process, generally with little or no consideration to life-cycle concerns.

Industrialised housing as one part of the construction industry in Sweden is identified to have the potential to increase efficiency and control, lower costs and increase quality (SOU 2002, 2000). The emerging industrialisation in construction follows an international trend, where Apleberger et al. (2007) and the Egan Report (1998) argue that construction must turn into a manufacturing process to become more efficient. Industrialised housing is part of the housing industry, but with a different set of characteristics regarding the dimensions:

- Process oriented vs. project orientation in design and production
- Prefabricated vs. site construction
- Many stakeholders vs. one evident process owner
Industrialised housing is said to avoid the characteristics of ordinary construction, though in actuality, they partly experience the peculiarities of both manufacturing and the project oriented one-of-a-kind building process, Figure 1.

Lessing et al. (2005) suggested eight characteristic areas that constitute the concept of industrialised housing: (1) planning and control of the processes, (2) developed technical systems, (3) offsite manufacturing of building parts, (4) long-term relations between contractors, (5) supply chain management integrated in the construction process, (6) customer focus, (7) use of information and communication technology (ICT), and (8) systematic performance measuring and re-use of experience. Lessing et al. (2005) proposed the level of fulfilment of these eight characteristics to measure the level of industrialisation. If all areas are developed a strong industrialised process can be created. The eight characteristics are also supposed to interrelate and balance each other, making it difficult to expect any high implementation of, e.g. the reuse of experience when the use of ICT is low. Lessing (2006) proposes a definition of industrialised housing that is connected to the eight characteristics:

*Industrialised house-building is a thoroughly developed building process with a well-suited organisation for efficient management, preparation and control of the included activities, flows, resources and results for which highly developed components are used in order to create maximum customer value.*

This definition includes a wide range of prefabrication strategies and emphasises process, organisational and technological aspects, as well as controlled processes. However, it does not exclude, e.g. on-site factories. This is somewhat different from the notion that a prefabrication strategy changes construction companies from object-oriented builders that focus on on-site construction to process-oriented manufacturers that take a larger control of the value chain with the reduction of workflow variability due to repetition in operations (Höök, 2006). Höök (2006) states that industrialised housing, when aiming for standardised and predictable processes, changes the company culture from organisational learning and learning between projects towards gradually building in knowledge into the process instead of in the people, thus facilitating consistent knowledge feedback. The degree of prefabrication ranges from manufacturing open walls and floors to producing entire volume modules with complete interior finishing, see Figure 2.
To manage the necessary changes, industrialisation of the housing industry requires a cultural alteration towards a Lean culture in industrialised housing, as proposed by Höök (2008). Industrialised housing production shares scheduling problems with regular construction, though it has the advantage of a dry working environment and above all traceable defects in production and design because the companies own the entire construction process.

1.1.1 Timber framed volume prefabrication

The concept of timber framed volume prefabrication is chosen in this study as the level of analysis and is therefore presented. The system is not analysed, but identified and presented as a well-defined form of production and a stable manufacturing industry in Sweden. A definition of industrialised housing from Höök (2008) describes the timber volume prefabrication strategy:

*Production is done in a closed factory environment, where only assembly and some finishing are performed at the construction site, with one owner of a specific process who has a clear goal of selling, producing and delivering a product based on repetition in housing design and production.*

This definition does not incorporate prefabrication through on-site factories, but it is open regarding the product, i.e. applicable to various prefabrication strategies. Some distinct characteristics can be derived from this definition of industrialised housing, see Figure 4:

- Manufacturing in a closed environment
- Only assembly on-site
- One distinct process-owner
- A goal of repetition in design and production

The method of using volume-based timber construction, as a prefabrication strategy, moves 90% of the work to factories (Höök, 2008). Theoretically, such companies have all the prerequisites to control the processes and the resources used, moving value-added activities up the supply chain and into a controlled environment (Nasereddin et al., 2007). The development of timber frame prefabrication in the multi-storey market was enabled through the introduction of functional building codes in 1994. The high strength/weight ratio for wood implies the possibility to handle prefabricated units over large transportation distances (Höök, 2006). In the basic view of timber framed volume prefabrication in this thesis, the house is a manufactured product, expected to satisfy the long-term demands of the customer as well as internal production efficiency demands. The hypothesis is that the technique of timber framed volume prefabrication has advantages concerning quality, maintenance and utilization of resources. A group of companies have chosen to utilise a timber framed volume prefabrication strategy to produce multi-storey houses and commercial buildings on the Swedish market,
INTRODUCTION

holding a 10 % market share. They are identified and chosen as the level of analysis in this thesis, Figure 3.

Figure 3. Timber framed volume prefabrication as part of the construction industry

The actual production process in industrialised timber framed volume prefabrication begins in the sales process requiring around 4 weeks (for a 20 apartment house), followed by the design phase of 20 weeks, and the production (manufacturing) phase of only 4 weeks. Assembly of a house on-site takes from 1 to 4 days (depending on the size), but the on-site finishing (installations, etc) requires another 4 weeks. Of the total production time for a volume element house, 80-90 % occurs in the factory or within the assembled house on-site, both with indoor conditions. Figure 4 presents a general view of the housing production process.

Figure 4. Production process for timber framed volume prefabrication

The building system is based on timber framed volumes that are prefabricated, where the timber framed volume is a closed three-dimensional structure constructed of floor, roof and wall elements. The production phase for a single volume is divided into three main stages (see
INTRODUCTION

Figure 4): (1) Wall, roof, floor element production, (2) volume assembly and (3) volume completion. Work is based on craftsmanship with hand-held tools and factories with static workstations, where elements such as interior roofs, floor structures, partition and volume separating walls are manufactured. After the frames of the elements are finished first, the electrical installations are placed inside and the elements are insulated. Boards are then placed on the frame to seal out the elements. Window panes and doors are assembled to the frames early in production; hence, the windows must be ordered as soon as sales are completed due to long delivery cycles. The finished wall elements are affixed onto the floor structure element and the roof element is placed on top. The volumes are completed with flooring, finishing, installations, wardrobes, cabinets and white goods. The completed volumes are then covered with moisture-proof tarpaulins before transport by truck to the construction site. A sub contractor usually produces the foundation at the same time, in-situ or as prefabricated slabs, to be ready to use when the volumes arrive on site. The volumes are assembled into the complete house at the construction site, on top of the already fabricated foundation. In the case of timber framed volume prefabrication, it is not a question of whether it is a preferable or possible strategy so much as to scrutinise its current state and recognize its level of success or failure. The nearness between the production unit and the design staff gives completely new possibilities connected to experience feedback compared to ordinary construction.

1.2 Aim and research question

The overall aim of this thesis is to investigate product quality through experience feedback at an aggregated product level in industrialised construction. The ISO 9000 standards together with the ISO 15686 standard for Service Life Planning and theories of Lean production/construction and TQM are chosen when performing the analysis. The level of analysis chosen is a group of companies that utilise timber framed volume prefabrication as their production strategy when producing for the Swedish market. The hypothesis of viewing houses as products instead of projects is based on the understanding and view of how industrialised housing can benefit from Lean and quality management theories. Industrialised housing through prefabricated timber framed volumes is a production form that should be well suited when utilising experience feedback. Based on the overall aim two research questions are formulated:

1. How can experience feedback support product quality in industrialised housing?
2. How is experience feedback utilised in industrialised housing?

1.3 Demarcations

The hypothesis that the technique of timber framed volume prefabrication having advantages concerning quality, maintenance and utilization of resources is not tested in this thesis, it is proposed. Instead, the focus of this study is experience feedback and product quality in the industrialised housing industry. Three major theories are identified, of which two are supported by ISO standard, i.e. the ISO 9000 series and the ISO 15686 series, which are the only standards mentioned in this thesis. The four companies chosen for the investigation are identified as industrialised, according to the definition of Höök (2008), which is by no means an indication of company efficiency or effectiveness, but rather a product and production strategy. Therefore, onsite factories are excluded in this thesis, even if it could be argued as possessing industrialisation characteristics.

The investigation was conducted from February 2006 to February 2008. The production process from design to assembly is only investigated, without any supply chain, logistics or economy. The companies are all small and medium-sized prefabrication companies that focus on timber framed volume prefabrication for the Swedish market. The investigated companies
represent one of two types of timber volume prefabrication housing in Sweden. This thesis deals with prefabricated commercial and multi-storey houses, but does not consider single family housing, i.e. detached houses for private consumers. Both detached housing and industrialized housing for commercial, multi-family and multi-storey buildings make use of timber as a load-bearing structure, and their production processes are similar. The main difference is found in the characteristics of the client and the functional/technical requirements of higher buildings – detached housing companies produce houses to private consumers, whereas customers of industrialized timber framed volume housing are mostly real estate trustees and municipalities. Timber framed volume prefabrication has dominated the market of single family housing, i.e. detached houses for private consumers since the 1970s and cost efficient production skills. Nevertheless, this thesis is concerned with the professional client representing the significantly larger part of the construction market, where multi-storey housing and commercial buildings have professional clients, real estate trustees and municipalities that conduct repeated procurement using different technical and functional requirements to those of single family dwellings.

The customer referred to in the thesis is not the private end customer or tenant, if not stated, but rather real estate trustees and municipalities, called clients in construction. The internal company customers are not defined, but recognised for further investigations. The defect study in this thesis is concerned with what effects product quality and lack of investigation regarding building pathology have on the resulting extensive structural failure. When attempting to improve industrialised housing, production issues concerning a cultural alteration, i.e. as proposed by Höök (2008), that are required in relation to the existing traditional culture in the construction industry arise, but are not dealt with in this thesis.

1.4 Structure of the thesis

This thesis comprises six chapters and four appended papers.

Chapter 1 to 6:

Chapter 1: Introduces the reader to the research area, describes and motivates the level of analysis, presents research aim and research question and presents the structure of the thesis.

Chapter 2: Contains the theoretical framework and presents a model of analysis to support Chapter 4 result and analysis.

Chapter 3: Presents the chosen methods for collecting the empirical results in papers I-IV and from additional investigations in connection to paper I.

Chapter 4: Presents and analyses the empirical results from papers I – IV, as well as from a complementary study presented in chapter 3.

Chapter 5 Discusses the result in relation to papers I-IV and Chapter 2.

Chapter 6: Presents conclusions based on findings related to the aim and answers the research question and proposes a conceptual model for feedback in industrialised housing.
INTRODUCTION

Appended papers I - IV:

**Paper I:** *Sustainability in Industrialised Wood Construction*

Written by John Meiling and Helena Johnsson, published in the proceedings from the Nordic Workshop in Wood Engineering, February 22, 2007, Skellefteå, Sweden. John Meiling’s contribution to this paper was co-planning the case study, conducting and planning the literature study and interviews. Both authors contributed with fundamental ideas. John Meiling wrote the paper, with supervision and feedback from the co-author.

**Paper II:** *Experience Feedback at Industrialised House Builders*

Written by John Meiling and Helena Johnsson, published in the proceedings of the 16th Annual Conference on Lean Construction, July 16-18, 2008, Manchester, England. John Meiling’s contribution to this paper was formulating fundamental ideas with the co-author, planning and performing process mapping, archival studies and interviews. John Meiling wrote the paper with feedback and support from Helena Johnsson.

**Paper III:** *Feedback in Industrialised housing – why does it not happen?*

Written by John Meiling and Helena Johnsson, published in the proceedings of the 24th ARCOM Annual Conference, September 1-3, 2008, Cardiff, Wales. The empirical input was gathered in paper II, and processed, categorised and analysed by John Meiling. John Meiling wrote the paper with feedback from Helena Johnsson. Awarded best Ph.D. student paper at the ARCOM conference in Wales.

**Paper IV:** *Defects in Industrialised Housing*

Written by Helena Johnsson and John Meiling, submitted for publication in Construction Management & Economics (Taylor & Francis) 2008. John Meiling’s contribution to this paper was to conduct literature study regarding defects in construction, and gather data from audits for statistical analysis. Helena Johnsson conducted the statistical analysis and wrote the paper.
2 THEORETICAL FRAMEWORK

The chapter aims to explore the theoretical fields that support quality enhancement in Swedish industrialised multi storey- and commercial housing production. The outlined fields are Lean production and Lean construction, Total Quality Management, Service Life Planning and a theoretical overview of information feedback and defect studies. The chapter ends with a model of analysis explaining how theory is connected to the investigated problem of feedback information.

2.1 Lean concept

The Lean production concept was introduced 1990 by Womack et al. (2007) in the book *The machine that changed the world*. The book was a result of a five year benchmarking study conducted at Massachusetts Institute of Technology (MIT), regarding car production all over the world. The machine that is referred to in the title of the book is Toyota’s product development, supplier management, customer support, and manufacturing processes collectively. Lean production is thus based on, and influenced by, the development of the Toyota Production System (TPS) created by Taiichi Ohno in the 1950s (Ohno, 1988). TPS and Lean production are actually different descriptions of the same concept but TPS is related to the Japanese manufacturing culture and Lean manufacturing/production is related to a view in USA of what TPS consists of. The basic definition of Lean seems to differ but it is often comprised to: “Lean is about waste elimination and value creation” (Womack et al., 2007). The key characteristic is the use of less resources, as input to a less demanding manufacturing process, and demand for higher performance as output, in return enhanced customer satisfaction leading to higher market share (Katayama and Bennett, 1996). The lean concept is considered by others to be too extreme for the western world, only suitable for the Japanese industry and the customer benefits for efficiency in production is questioned by Green (1999). In the book *Lean thinking* Womack and Jones (2003) is completing the Lean theory by presenting five guiding Lean principles of production: (1) value, (2) value stream, (3) flow, (4) pull, and (5) perfection, see Table 1.

Table 1. Lean principles of production, developed from Björnfot (2006)

<table>
<thead>
<tr>
<th>Principle</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specify value</td>
<td>Provide the value actually desired by the customer</td>
</tr>
<tr>
<td>Identify the value stream for each product</td>
<td>Identify, for each product, the sequence of actions needed to bring value to the customer</td>
</tr>
<tr>
<td>Make the product flow without interruptions</td>
<td>Line up the steps in the value stream in a continuous flow, everything disturbing the flow or not adding value is waste.</td>
</tr>
<tr>
<td>Let the customer pull value from the producer</td>
<td>Let the customer ask for the product or service and then work backwards to bring the product, i.e. pull value from the firm</td>
</tr>
<tr>
<td>Pursue perfection</td>
<td>An endless search for eliminating waste</td>
</tr>
</tbody>
</table>

These Lean principles are best mastered when the importance of people is recognised (Womack and Jones, 2003). This is an important difference while comparing Lean methodology to other improvement methodologies such as Just-In-Time (JIT) and Total Quality Management (TQM). Lean is presented by its advocates (Womack and Jones, 2003) as the third significant production form after craft production (one-piece flow) and mass production (by Henry Ford). The Lean epithet is chosen because lean production uses less of everything compared to mass production. Further it is said to result in fewer defects while producing a growing product variety (Womack et al., 2007). To achieve this, work should focus on manufacturing, product development, supply and distribution. Liker (2004) published *The Toyota Way*, where fourteen management principles are presented that will aid companies in...
the transformation to become Lean (not to be confused with the 14 points presented by Deming (1986)). These principles are categorised in four groups, the four P’s often illustrated as a pyramid, namely: (1) Long term Philosophy, (2) The right Process will produce the right results, (3) Add value to the organisation by developing your People and partners, (4) Continuously solving root Problems drives organisational learning. The latter is to be implemented last, i.e. on top of the pyramid, and fundamental when trying to understand how quality can be enhanced by minimising defects and mistakes. The principles connected to the fourth group, problems, are (Liker, 2004):

- Go and see for your self to thoroughly understand the situation.
- Make decisions slowly by consensus, thoroughly considering all opinions; implement decisions rapidly.
- Become a learning organisation through relentless reflection and continuous improvement.

At Toyota seven major types of waste is identified as non-value adding in business and manufacturing processes, these seven wastes are complemented with an eighth waste by Liker (2004):

1. Overproduction. Producing items for which there is no order creates storage.
2. Waiting. Unproductive workers due to e.g. bottlenecks or stock outs.
3. Unnecessary transport or conveyance. Inefficient transport of goods or moving materials in or out of storage.
4. Over processing or incorrect processing. E.g. waste is generated when producing higher quality than required.
6. Unnecessary movement. Looking for, searching for, and reaching for tools or material. Walking is considered waste.
7. Defects. Production of defect parts or correction. Repair or rework, scrap, replacement production, and inspection mean wasteful handling, time, and effort.
8. Unused employee creativity. Losing time, ideas, skills, improvements, and learning opportunities by not engaging or listening to your employees thus are the waste of human potential.

Ohno (1988) considered overproduction as the fundamental waste since it causes most of the other wastes (Liker, 2004). The list of wastes is again complemented with making-do suggested by Koskela (2004). Making-do is defined as a situation where a task is started without all its standard inputs, or the execution of a task is continued although the availability of at least one standard input has ceased. The list of wastes is contributed also by Bicheno (2004) as doing the wrong product efficiently, this waste could be compared to not being able to fulfil customer requirements as stated in The Lean toolbox (1999).

Womack and Jones (2005) close the product life cycle by introducing Lean consumption, where also consumption is viewed as a process after design and production. Lean has been occupied with finding ways to create value for the customer by eliminating waste in design and production, but the product lifecycle includes maintenance and service in the consumption phase that also is dependent on a process flow to generate profit. The way to approach Lean when it is implemented could be tool-based or flow based. The tool-based approach is where Lean is similar to other improvement methods where a set of tools assist in the elimination of waste, increase in quality, lower production time and cost. Lean is being accused to have a tendency of focusing on training people in tools and techniques and at the same time focus too little on understanding the human factor and to build the right culture (Dahlgaard and Dahlgaard-Park, 2006). The flow based approach, supported by Toyota, represents implementation of flow in production, which exposes quality problems along with implementation,
making the flaws expose themselves. The tool based methodology focuses on getting things from the employees, when a true Lean company focuses on improving people and offers something to the employee (Veech, 2004). This leads us to the notion that Lean is two folded, with focus on both performance and people. Lean is implemented through management but getting the people to work is done by leadership (Mann, 2005, Dahlgaard and Dahlgaard-Park, 2006). A model for the development towards an effort to become Lean is proposed by Karlsson and Åhlström (1996) here briefly summarised in:

1. Elimination of waste: The purpose of the Lean production philosophy, that was developed at Toyota Motor Company after World War II, is to lower costs. This is done through the elimination of waste.
2. Continuous improvement: If the elimination of waste is the most fundamental principle of Lean production, then continuous improvement can be said to come next. The production system is constantly improved; perfection is the only goal. The constant strive for perfection even has its own word in Japanese, Kaizen.
3. Zero defects: Although quality in itself is an important performance variable in Lean production, it is also a prerequisite for the production system. To be able to attain high productivity, it is essential that all parts and products are fault free from the start. The goal is to work with products that are fault free through the continuous improvement of the manufacturing process. Thus, zero defects denote how a Lean company works in order to attain quality.
4. Just-in-time: Closely associated with zero defects is the principle of just-in-time, since accomplishment of fault free parts is a prerequisite to achieve just-in-time deliveries.
5. Pull instead of push: Closely related to the principle of just-in-time is the way in which material flow is scheduled, through pull instead of push.
6. Multifunctional teams: A multifunctional team is a group of employees able to perform many different tasks.
7. Decentralised responsibilities: The multifunctional teams are charged with the duty of performing tasks that previously were carried out by employees in indirect departments.
8. Integrated functions: This means that tasks previously performed by indirect departments are integrated into the team, increasing the work content of these teams.
9. Vertical information systems: Information is important in order for the multifunctional teams to be able to perform according to the goals of the company.

It could be concluded from this list a lack of managerial focus connected to implement continuous improvements and minimising defects. Faulty free means less expenses for waste, but a zero defect product could in fact be missing customer requirements. Höök (2008) defines a Lean culture based on the notion that overall goal of long term profit is a mean to suppress that actors are likely to favour their own part ahead of totality:

Shared assumptions that the common goal is increased long-term profit, achieved by decreased costs and waste (performance), through a focus on customers and the people that create value.

This is a distinct focus on cultural change from focusing solely on the customer and production towards a simultaneous change in the mindset of management and employees.
2.1.1 Lean Construction

With Lean production as a foundation a Lean application in construction was proposed by Koskela (1992) stating eleven Lean principles for the construction industry:

1. Reduce the share of non-value-adding activities.
2. Increase output value through systematic consideration of customer requirements.
3. Reduce variability.
4. Reduce the cycle time.
5. Simplify by minimizing the number of steps, parts, and linkages.
6. Increase output flexibility.
7. Increase process transparency.
8. Focus control on the complete process.
9. Build continuous improvement into the process.
10. Balance flow improvement with conversion improvement.

The eleven principles are well suited for industrialised production methods and a high degree of prefabrication, but the Lean construction community has focused more on site-construction and project management. Ballard (2005) argues construction to be a project production system and emphasises implications for considering construction as a type of manufacturing. Koskela (2000) introduces the transformation-flow-value (TFV) framework arguing that Lean principles from Womack and Jones (2003) only deal with flow of work in production. Instead production in construction should be viewed as transformation of inputs, value- and non-value adding activities, where the output is value to the customer. In Lean construction focus on individuals and people is subordinated to production performance, this critique is supported by e.g. Höök (2008), Björnfot (2006) and Bølviken (2007).

The concept of Lean in construction is in this thesis extended from the basic statement that Lean is about waste elimination and value creation to also add the importance of people in an organisation as part of a Lean culture (Mann, 2005, Höök, 2008, Andersen et al., 2008, Veech, 2004). Social aspects of production is absent within Lean Construction (Andersen et al., 2008), Liker (2004) states that Lean production primarily provides tools for people to continuously improve their work, meaning more dependence on people and again a focus on the social aspects of production. This approach converges very much with principles of learning and organisation vs. culture (Schein, 2004, Senge, 2006).

Vrijhoef and Koskela (2005) is revisiting significant peculiarities in construction production naming one-of-a kind production, temporary organisations and site production, see Table 2.

### Table 2. Peculiarities of construction according to Koskela.

<table>
<thead>
<tr>
<th>Peculiarities</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site production</td>
<td>I.e. Organising production around product dependent on outdoor conditions.</td>
</tr>
<tr>
<td>Temporary production</td>
<td>E.g. fragmented supply chain</td>
</tr>
<tr>
<td>organisation</td>
<td></td>
</tr>
<tr>
<td>One of a kind production</td>
<td>E.g. design to order and order based production</td>
</tr>
</tbody>
</table>

Bølviken (2007) initiates a discussion about industrialised production by slightly adjustment of the TFV paradigm (Koskela, 1992, Koskela, 2000) and the three peculiarities of construction by Vrijhoef and Koskela (2005), proposing that construction is production of commodities, possessing both use and exchange value, through a flow of transformations, rather than just transformation of value as such. This reasoning leads to a more differentiated discussion of
peculiarities with the introduction of basic and non-basic peculiarities. Vrijohef and Koskela (2005) discuss peculiarities in order to analyse industry related phenomena’s i.e. elimination or mitigation of peculiarities in order to avoid disadvantages. Bølviken completes the reasoning with a list of basic peculiarities, comparing them to the proposal of Vrijohef and Koskela (2005). See Table 3.

Table 3. Basic peculiarities, developed from Bølviken (2007).

<table>
<thead>
<tr>
<th>Basic peculiarities</th>
<th>Non-basic peculiarities</th>
<th>Consequence of basic peculiarities, optional i.e. possible to mitigate or eliminate</th>
</tr>
</thead>
<tbody>
<tr>
<td>From Bølviken (2007)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buildings or construction are:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fixed to the ground</td>
<td>1. Site production</td>
<td>Construction will always be a combination of on and off site production</td>
</tr>
<tr>
<td></td>
<td>2. One of a kind</td>
<td></td>
</tr>
<tr>
<td>Expensive</td>
<td>3. Temporary organisation</td>
<td>Due to the uniqueness of every project</td>
</tr>
<tr>
<td>Public interest</td>
<td>4. Laws and regulations</td>
<td></td>
</tr>
<tr>
<td>Projects</td>
<td>5. Different trades</td>
<td></td>
</tr>
<tr>
<td>Complex</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Takes time – last long</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The Lean strategy strives to stabilise variability and dependence in order to increase work flows and reduce waste, resulting in focus on exchange value (price) at the expense of use-value (product). This is supported by e.g. Dubois and Gadde (2002) where the system favours productivity within projects, while innovation suffers, e.g. as the management of the product towards profit with enhanced quality. Björnfot (2006) claims that the main driving force in the development of applications for Lean construction is improved control of the production process: stability (reliability) and better control (predictability) are sought through the reduction of variety in work practices and supply chains. Instead of a strict focus on flow characteristics the production could be seen as both a physical/logistical process producing use value as well as an economical process producing exchange value. Then e.g. Andersen et al. (2008) add the Social factor as production is always carried out by people. (Höök and Stehn, 2008) states that, the Lean culture is in conflict with the traditional construction culture. Furthermore (Höök and Stehn, 2008) state that in order to achieve long term benefits from Lean applications people have to be motivated both by a working strategy and visible quality management.

2.2 Service Life Planning

This section presents the background and main features of Service Life Planning and some of its applications so far in construction.

During the last decades there have been an increased interest and focus on the needs to determine durability and service life of materials, components, installations, structures and ultimately buildings. But why is there still no impact on a company level? A performance based building code can in fact stipulate quantitative requirements for the service life of construction products, as in the case of New Zealand (Hovde, 2000). European Parliament Council Directive 89/106/EEC, from 21 December 1988, is most known as the CPD (Construction Product Directive). The CPD is described as an approximation of laws, regulations, and administrative provisions relating to construction products. Elimination or Minimisation of trade barriers is one reason for implementing the CPD. The term construction products means any product which is produced for permanent incorporation in construction works, including both
building and civil engineering works (European-Parliament, 1988). In annex I in the CPD six essential requirements are summarised:

1. Mechanical resistance and stability.
2. Safety in case of fire.
3. Hygiene, health, and the environment.
4. Safety in use.
5. Protection against noise.

The implementation of the CPD initiates a whole life perspective to construction as it requires that the six essentials shall be met “during an economically reasonable service life”. The term service life is defined as period of time after installation during which a building or its parts meets or exceeds the performance requirements (ISO 15686-1:3.1.1). Guidelines for this implementation is formulated within the ISO 15686, and its ten parts, aiming for quality-increasing Service Life Planning (SLP) of buildings and constructed assets, where SLP is defined as preparation of the brief and design for the building and its parts to achieve the desired design life, for example in order to reduce the costs of building ownership and facilitate maintenance and refurbishment (ISO 15686-1:3.1.7). Design life is defined as the service life intended by the designer (ISO 15686-1:3.1.4). The standardisation work was initiated in 1993 and today the series ISO 15686 is composed of ten parts with six published parts so far, Table 4.

Table 4. The parts of ISO 15686 standard for Service Life Planning.

<table>
<thead>
<tr>
<th>ISO 15686</th>
<th>Description</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (2000)</td>
<td>General principles</td>
<td>Published</td>
</tr>
<tr>
<td>2 (2001)</td>
<td>Service life prediction procedures</td>
<td>Published</td>
</tr>
<tr>
<td>3 (2002)</td>
<td>Performance audits and reviews for implementation of SLP</td>
<td>Published</td>
</tr>
<tr>
<td>4 (-)</td>
<td>Data requirements for service life determination</td>
<td>-</td>
</tr>
<tr>
<td>5 (2008)</td>
<td>Whole life-cycle costing</td>
<td>Published</td>
</tr>
<tr>
<td>6 (2004)</td>
<td>Procedures for considering environmental impacts</td>
<td>In review stage</td>
</tr>
<tr>
<td>7 (2006)</td>
<td>Performance evaluation for feedback of service life data from practice</td>
<td>Published</td>
</tr>
<tr>
<td>8 (2008)</td>
<td>Reference service life and service-life estimation</td>
<td>Published</td>
</tr>
<tr>
<td>9 (-)</td>
<td>Guidance on assessment of service-life data</td>
<td>In approval stage</td>
</tr>
<tr>
<td>10 (-)</td>
<td>Levels of functional requirements and levels of serviceability, Principles, measurement and use</td>
<td>In committee stage</td>
</tr>
</tbody>
</table>

When presenting the set of ISO 15686 standards in the ISO standard handbook a comparison is made with manufacturing products or more precise a comparison between cars and houses is made. Methods for standardisation and prefabrication have been thoroughly implemented in the car and truck industry, but application of similar mechanisms to buildings and constructed assets is not straightforward, due to the five, partly interacting, reasons (Jernberg, 2005), see Table 5. The main purpose of Service Life Planning is to ensure that functionality is maintained throughout the building’s intended service life at predictable costs (which will depend on the building’s average annual maintenance costs and service life).
The standards emphasise the importance of a systematic approach regarding briefing, design, production and ownership. The base is instead the estimation of service life of the building elements and therefore it addresses the durability aspects of housing material and products. When this is established it is easier to be inspired of the standard composition, methodology and background as it supports the importance of feedback in the housing industry. The standards also have a very useful terminology to express the fundamentals in the construction process; this will be treated later in this section. Focus for prediction is substitutability in the building as non-substitutability i.e. permanent elements is required to last at least as long as the service life of the building itself. The basic idea to balance requirements, expected lifecycle costs, environmental impact and durability data and thus conceive a specific or reduced cost of building ownership seems reasonable. But the house is a complex construction. Brand (1994) suggests the unit of analysis to be changed from the building to the use of the building over time, and this is suggested to be the real design problem. This is a much better explanation regarding the incentives for implementing Service Life Planning. One way to conceive a building is to describe it, not as an entity but rather as several layers of service life of built components (Brand, 1994). The layers presented is related to the hierarchy presented by Trinius and Sjöström (2005) i.e. material, component and structure:

- Site (Geographical setting) Eternal.
- Structure (Foundation, load bearing elements) – 30 to 300 years.
- Skin (Exterior surface) – 20 years.
- Services (HVAC, elevators, escalators) – 7 to 15 years.
- Space plan (Interior layout, meaning walls, floor, ceilings, doors) – 3 to 30 years.
- Stuff (Interior design and all the things we use) – daily to monthly.

Brand (1994) states that over a period of fifty years, the changes within a building cost three times more than the original building, suggesting that architecture is of little importance. This kind of thinking is supported by Ridder and Vrijhoef (2008) stating that the architect no longer works for the client, but rather for the supplier:

*If you buy a car, you don’t go to the dealer with a car designer.*

The first part in the standardisation series describes terms concerning service life, forecasting and what has to be done to achieve a service life forecast process. There are three fundamental levels of assessment of probable service life: (1) Predicted-, (2) estimated-, and (3) forecast – service life. The interrelations are illustrated in Figure 5 below. The first, predicted service life is obtained by the systematic methodology described in part two of the ISO 15686 standard. The second, estimated service life, is obtained through other, approximative methods, one of

<table>
<thead>
<tr>
<th>Implication elements</th>
<th>Construction industry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complexity</td>
<td>A modern building is a complex system of materials, options regarding design and interactions between the two.</td>
</tr>
<tr>
<td>Uniformity regarding product</td>
<td>Constructed assets normally differ even if similar, due to basic peculiarities, i.e. fixed to the ground.</td>
</tr>
<tr>
<td>Uniformity regarding production</td>
<td>Fairly low automation combined with a weak co-operation between actors where the product has no brand.</td>
</tr>
<tr>
<td>Service life</td>
<td>A building or constructed asset is supposed to last for 50 – 100 years.</td>
</tr>
<tr>
<td>Environment</td>
<td>The microenvironment, even between two close locations, can differ dramatically. Houses do not move.</td>
</tr>
</tbody>
</table>
which is the so-called factor method (Marteinsson, 2003) not treated in this thesis. The third, forecast service life is a collective term for both predicted and estimated service life, not giving any hint of reliability. These three levels are complemented with yet two others: (a) design life, and (b) reference service life. The first describes what the forecast will be compared with and is called intended service life by the designer. The last term is also a probable service life serving as input when adopting a service life to a specific in-use condition, see Figure 5.

Theoretical Framework

The Service Life Planning process is described in the first part of ISO 15686, see Figure 6. Thus the framework is presented but not the interfaces between material, components and structures. It is here implied that a full investigation for a whole building is not realistic. In Hed (2003) four examples are presented, of totally 30 investigated items or materials, of the Service Life Planning regarding a housing project, given examples is not followed by motivation of choice and consist of: (1) metallic flashing components, (2) façade rendering, (3) interior gypsum board (4) concrete structure. These are stochastic observations without any methodology considerations regarding priority.

Figure 5. Basic terms for service life forecast.

The Service Life Planning process is described in the first part of ISO 15686, see Figure 6. Thus the framework is presented but not the interfaces between material, components and structures. It is here implied that a full investigation for a whole building is not realistic. In Hed (2003) four examples are presented, of totally 30 investigated items or materials, of the Service Life Planning regarding a housing project, given examples is not followed by motivation of choice and consist of: (1) metallic flashing components, (2) façade rendering, (3) interior gypsum board (4) concrete structure. These are stochastic observations without any methodology considerations regarding priority.
15686-1) together with part two and three a full understanding of the intended use can be obtained from collection of prediction data to conduct the planning process and finally audit and review to monitor that necessary measures will be implemented to obtain desired performance over time. Clause 8 in ISO 15686-1 describes how prediction data is transformed into a forecast based on exposure and performance evaluation, which is described in detail in the entire second part of the standard. When this is not possible some estimation is required and this is described in Clause 9 i.e. the factor method. The Service Life Planning process is an extensive attempt to systematise the construction process thus the logic of 15686 follows the construction process. But it does not connect to the housing industry, as it has no receiving or organised instance at the performing companies. So far the work within Service Life Planning has been criticised of being devoted to durability and to the factor method (Davies and Wyatt, 2004). This can be exemplified with the extensive work of Marteinsson, summarised in his thesis from 2005 and in the State-of-the-art report by Hovde from 2000 (Marteinsson, 2005, Hovde, 2000). As Service Life Planning is pictured to be a natural and important part of building and construction, the market is said to be closing up to getting ready for implementing Service Life Planning. Marteinsson struggles to demonstrate the practical use of the factor method and states some important criteria’s for service life information in construction (Marteinsson, 2005):

- Service life information should be available in the design stage as a cornerstone in Service Life Planning.

- Service life information should also be directly comparable when making a design choice between material and components.

This is to ensure later service ability and planning for maintenance during operational phase, but foremost to ensure acceptable life cycle costs. But it is also stated that the information needed in the design stage is not yet available, thus the interest in simplification and the factor method, resulting in less reliable estimations of service life and ultimately poor cost estimations. The market will probably wait for more extensive product information before the attempt to conduct a thorough Service Life Planning. Implying there exist a gap currently between intended and actual, see Figure 7.

Figure 7. The gap towards practitioners

Simplifications and methods for practitioners are yet to come. In housing a more limited use can be foreseen regarding e.g. cladding (Shohet and Paciuk, 2006), windows (Marteinsson, 2003) and roofs. The estimated service life is always just predictions and does not give any assurance of the actual service life. The reference service life determined under well-defined conditions is the starting point of the method, which is then adjusted by some modifying
factors to comply with the specific conditions. Service Life Planning then puts focus on the commission of houses and on how design should be conducted in order to encompass overall operation and maintenance requirements. As both client and authorities have some ideas about the service life length on a system or building level, and materials have some applications where a reference service life is to be expected but on a component level it is very hard to get information of service life. All buildings are in some respects unique and this inevitably influence both planning and design of the buildings regarding Service Life Planning assessment. The natural driver for requirements regarding service life is codes and standards as there are rigorous demands for components that form a part of the structural system. Other parts may be subject to voluntary requirements by the client/owner but this is not utilised within the investigated companies. Authorities do not require special reliability of other parts of the construction. This results in the lack of a whole life perspective regarding maintenance, repair and cost. The reasons for service life termination are numerous: technical, economical, functional, social but technical faults are perhaps the only one resulting in safety risk. Non-technical reasons are not predictable in the same way as technical reasons. Examples given are wall claddings and windows, various test pieces in wood and metal.

The various components of a building may be grouped into three object categories where it is possible to level the efforts regarding Service Life Planning (Marteinson, 2005):

1. High risk: e.g. structural parts, faults will result in major cost or risk to health.
2. Medium risk: e.g. heating and ventilation, faults will result in inconvenience or moderate economical risk, requires immediate attention.
3. Low risk: This is the larger parts of components in a living house. Here is great need for comparison of products.

The requirements for precision and reliability will vary depending where the component is located with regard to the risk taken. So far this is done based on experience, and it is the responsibility of each constructor to assimilate lessons learned. Each housing company could have a database for experiences feedback regarding material and components that could be utilised for regarding design of the next object. Häkkinen (2007) outlines a future state, and presents an example of how information can be stored and distributed under the name of LifePlan (2006). Information is available both for the design phase, and for the operation and maintenance phase. The information given is technical service life information based on supplier information. A more performance based approach is investigated and suggested by Trinius and Sjöström (2005), which describes the interrelation between material, component and building with regard to service life considerations, Figure 8.

They pinpoint the difficulty to meet client performance requirements rather than just comply with the product and material standard at hand, which results in less innovative solutions. The concept of performance based building has been extensively investigated during the years 2001-2005 and is summarised in an international state of the art report (Becker et al., 2005). This report outlines and proposes the path to be taken in the future, Implying yet another 10
to 20 years of work before ICT based information can be available. A future state according to Häkkinen (2007) is to work with building construction information databases.

Most of the work with SLP and ISO standard 15686 has been occupied with the methods at hand for estimating service life of building products. This is in the interest of component manufacturers seeking systematic methods to assess the risk to premature deterioration of existing products in given specific climate effects (Lacasse and Sjöström, 2003). The authors also stress the importance of relating service life information to the system level of interest i.e. building-, component-, or material level. As methods for determining service life is developed (Lacasse and Sjöström, 2004) there is still a gap where the practitioners try to achieve a performance based design to the client and within the contract at hand. The lack of support, for Service Life Planning, from current product standards results in difficulty to manage products through standards, which is emphasised by e.g. Sjöström et al. (2002). Models for assessment of reference service life are proposed by Strömberg (2003) implying there is no complete set of reference service life at hand for housing companies. The importance of product specific information to be available is stressed also by Häkkinen (2007), the lack of databases and existing routines are to blame for ignoring to collect the information needed, Figure 9. The industrialised housing firms are more suited to utilise gathering of performance data into a company database, as they control the products used in the timber framed volume prefabrication strategy, but it is not fully grasped and not implemented.

![Diagram](Figure 9. Support for Service Life Planning at company level is an imperative for making ISO 15686 effective according to Häkkinen (2007).)

### 2.3 Product quality and quality management

A company is dependent on customers and it is therefore important to provide products that the customers are willing to pay for. It could be said that the ultimate goal is to provide value to external customers, while Lean focus on internal customers. Hence the customer or the market settles the quality of a product. The manufacturing industry has been working with different aspects of quality for many years, starting in the 1950s. It has been recognised through best practice over time, through the work of successful companies as an imperative strategy for improving profitability and in this thesis seen as a catalyst for focusing mainly on product effectiveness, while Lean here is understood to have focus on efficiency. The company that can increase product quality and meet customer demands better than its competitors on the market is more equipped to become successful and profitable. But the clear focus on external customers does not imply to degrade the internal customer. This has been proven to be true whether it is a manufacturing- or service company. The word quality has its origin from the Latin word qualitas meaning character, product quality is here being defined as:

*The quality of a product is its ability to satisfy, and preferably exceed, the needs and expectations of the customer* (Bengman and Klevfjö, 2003).

Even if there are numerous definitions of what the term quality really means (Garvin, 1984) this definition incorporates the important fact that it is not enough to satisfy customer expectations as they are stated in e.g. product requirement listings from the customer, but in...
order to be successful quality should also exceed expectations. But the organisation that provides the product is also judged and the product is only one part of the customers total quality experience. This leads to the notion that quality is a relation between a product, its underlying organisation and the customer, Figure 10.

Figure 10. Quality vs. organisation, product and customer, developed from Bergman and Klefsjö (2003)

A set of product quality dimensions are proposed by Bergman and Klefsjö (2003) accordingly:
- Reliability
- Performance
- Maintainability
- Environmental impact
- Appearance
- Flawlessness
- Safety
- Durability

These dimensions are then examples of what the customer really comprehend. These dimensions are also a source of strategic choice for the company, maybe it is not possible to compete in all the quality aspects (Garvin, 1984). In order to manage quality in this context on a competitive market place where customers are prepared to pay less for enhanced demands regarding requirements, a Total Quality Management approach and continuous improvements have evolved.

2.3.1 Total Quality Management

Quality in production, i.e. the quality story (Dahlgaard and Dahlgaard-Park, 2006), spans over the lion share of the twentieth century, with focus on time post World War II, contributed both by eastern and western scientists and consultants. Thus when describing the quality movement and quality management principles there is not one single truth, but rather various views and different ways of evolvement over the years describing quality management and how quality practice is to be conducted. A fairly resent definition of TQM, preferred in this thesis, is presented by Hellsten and Klefsjö (2000) accordingly:

\[ TQM \text{ is a continuously evolving management system consisting of core values, methodologies and tools, the aim of which is to increase external and internal customer satisfaction.} \]

This could be compared to the definition of Total Quality Control stated by Feigenbaum (1991), pointed out as one of the inventors of TQM:
Total quality control is to provide genuine effectiveness and control by identification of customer quality requirements and end only when the product has reached the customer and he is satisfied.

Total Quality Management (TQM) is defined as both a philosophy and a set of guiding principles (Dale 1999, Bergman and Klefsjö 2003). The values of TQM is summarized in five cornerstones or core values; (1) focus on the customer, (2) base decisions on facts, (3) focus on processes, (4) improve continuously, and (5) let everyone be committed (Dale 1999). The cornerstones are supported by a set of techniques and tools (Bergman and Klefsjö 2003), many of which are also used within the Lean production system (Arnheiter and Maleyeff 2005).

According to Hellsten and Klefsjö (2000) the TQM system should be executed in three steps where the first establishes the core values. Secondly techniques should be identified that are suitable for the organisation to use and that supports the values. The third step is to find tools that can be used in an efficient way to support the chosen techniques, see Figure 11.

The introduction of TQM marks the era later called the second generation of quality management (Foster and Jonker, 2003). The first step was characterised by focus on inspections of the finished output. The quality awakening in the western world is often said to descend from a period of time when the manufacturing industry went from craft- to mass production. The entry key to TQM is often said to be ISO 9000 standards that was written to provide guidelines to assist organisations in implementing and operating a Quality Management System (Poksinska, 2006). The level of quality consciousness in general is said to be reflected and supported by the international organisation for standardisation (ISO, 2000) and is formulated in the ISO 9000-series, a set of standards concerned with what a company’s quality system should include and how it should be implemented (Poksinska, 2006, Nee, 1996). Four stages is proposed (Dale, 1999, Bergman and Klefsjö, 2003) and have been detected as leading the way towards a Total Quality Management approach: (1) inspection, (2) quality control, (3) quality assurance and (4) Total Quality Management, see Figure 12.
The first step is characterised by simple in-house, inspection based, after-the-event and no prevention content actions aiming for quick fix actions on the output. The second, quality control, step is an improvement because the requirements are more detailed, feedback is present and there is focus on detection. The definition of quality control according to ISO standard (ISO, 2000):

*Part of quality management focused on fulfilling quality requirements.*

As a permanent working state this detection or fire-fighting mode is aimed at finding the non-conforming product, but it does not prevent it from being made. The third step is quality assurance and it is characterised by finding the root cause of a problem rather than just switching the blame, Figure 13. The ISO standard definition (ISO, 2000):

*Part of quality management focused on providing confidence that quality requirements will be fulfilled.*

The requirements of the ISO 9000 standards are seen as a minimum state for this level, also the use of e.g. the seven quality tools: (1) Histograms, (2) check sheets, (3) pareto analysis, (4) cause and effect diagrams, (5) graphs, (6) control charts, (7) scatter diagrams.

This level is the prevention based level (Dale, 1999), which means that defects are identified as early as possible in the process and continuous improvements, often demonstrated by the PDCA (Plan, Do, Check, Act) learning cycle (Deming, 1986), by improvement tools and methods, such as root cause analysis (RCA), (Wilson et al., 1993, Jones et al., 1999, Arnheiter and Maleyeff, 2005), and techniques like cause-and-effect- and tree diagrams. The forth and highest level according to Dale (1999) is that of TQM, and it involves the application of quality management principles in all aspects of the organisation including customers and suppliers.

Yet another way to describe the quality transformation is the Juran Trilogy (Juran and Gryna, 1988) where it is presented in the form of a trilogy of managerial processes analogue with...
finance management, namely the phases of: (1) Quality Planning; Create a process that will be able to meet established goals and do so under operating conditions (2) Quality Control; Keep the waste from getting worse; meet quality goals during operations and (3) Quality Improvement; Breaking through to unprecedented levels of performance, see Figure 14. The phases are interrelated and aims to find what the author calls fitness for use which is basically the same as quality in the product.

Figure 14. The Juran quality trilogy

A Quality management system is defined to direct and control an organisation with respect to quality (ISO, 2000). The Implementation of a quality management system is an extensive commitment for the company and yet there is no certain outcome (Landin, 2000). The level of quality consciousness in general is reflected and supported by the international organisation for standardisation (ISO, 2000) and is formulated in the ISO 9000-series, a set of standards concerned with what a company’s quality system should include and how it should be implemented. The ISO 9000 logic for quality management is formulated in eight principles: (1) Focus on your customer, (2) Provide leadership, (3) Involve your people, (4) Use a process approach, (5) Take systems approach, meaning linking processes, (6) Encourage continual improvement, (7) Get the facts before you decide, (8) Work with your suppliers. Thus the quality management system approach should encourage the company organisation to analyse customer requirements, work with the processes that result in a product accepted by the customer and to continuously manage these processes towards improvement. A quality management system is supposed to constitute a foundation for continuous improvements in order to enhance interests of customers and other stockholders. But quality work at a company could also be conducted as a routine exercise without any thoughts of implementing a system for enhanced product quality (Nee, 1996). The result is then to manage documentation aspects of achieving or maintaining the ISO certificate rather than reaching desired quality goals (Gustafsson et al., 2001, Lam and Ng, 2005). Quality within the ISO standard is defined as the degree to which a set of inherent characteristics fulfil requirements, i.e. needs or expectations that are stated, generally implied or mandatory (ISO, 2000).

2.3.2 Quality and construction

Quality is certainly a complex and multifaceted concept. But it is also a source for confusion, managers at different levels frequently fail to communicate exactly what they mean by the term (Garvin, 1984), which results in an inability to show real progress on the quality front. Quality management within the construction sector has been intensified in recent years through customer demands and government legislation and attention. Laws and regulations have been sharpened in order to emphasise the importance of quality work and the introduction of the
quality concept, e.g. in a Swedish general construction regulation, AB94, which is a voluntary agreement between major Swedish stakeholder in construction, the concept quality plan and inspection plan was introduced the regulation of 2004 (AB, 2004). Changes in the Swedish building regulation (PBL), in 1995, gives the construction client full responsibility when it comes to the fulfillment of technical requirements (PBL, 1995). Authorities in Sweden require that construction companies should have certain knowledge of ISO 9001 (BFS, 1996), and an increased demand from clients for quality assurance leads to companies that only succeed to implement a top-down quality approach because of the reason for adopting quality management principles and routines spring from a desire not to loose customers (Dale, 1999, Gustafsson et al., 2001, Poksinska, 2006). Low and Peh (1996) suggest a framework for implementing a TQM quality system in construction, though the impediments are also summarised by Low and Teo (2004), who state that the success of TQM is yet to be proven in construction. Barriers to quality improvement efforts are numerous e.g. failure to correctly understand customer requirements, both internal and external, failure to understand the capability of the production system, failure to track defects, failure to repair sub optimised processes and failure to track quality costs (Sower et al., 1999). This is to blame on management according to (Deming, 1986) and the second reason is communication.

When comparing the thought of a building as a product it is no difference if utilising a high degree of prefabrication and control compared to when the degree of offsite construction is higher. Both production methods produce a house that can be defined as a product. According to ISO standard (ISO, 2000) a product is defined as the result of a process and divided in four generic categories namely:

1. Services
2. Software
3. Hardware
4. Process materials

A product can consist of several categories connected to its dominant part; a car or a house is typically all four categories. A project is defined, in the same standard, as a unique process where the outcome may be a product. This thesis does not promote the prefabrication and industrialised housing concept as such, but tries to scrutinise industrialised housing possibilities and investigate how it is performed regarding experience feedback and product quality.

2.4 Continuous improvements

The importance of improvements through feedback is thus demonstrated in sections 2.1, 2.2 and 2.3, as feedback and continuous improvements are the cornerstones of Lean production, Service Life Planning and Total Quality Management and where the two latter are supported by the ISO standard. As the foundation for continuous improvements and feedback is a crucial function to grasp for the company aiming for profit and customer satisfaction. Improvements are defined by Juran (1988) as the attainment of a new level of performance that is superior to any previous level, as visualised in Figure 14 above, the random problems should then be detached from the chronic problems in order to realise the current level of quality in production. According to Imai (1986) improvements can be defined by the term Kaizen together with innovations. Kaizen equals maintaining and improving the work-standard through small, gradual improvements and innovation is thorough improvements as a result of large investments. It is vital to make a difference between innovation and Kaizen, where the former is more active as a separate process prior to design and the latter is more focused on production, Figure 15.
Theoretical Framework

![Diagram showing the interrelation between innovation, design, and feedback, developed from Imai (1986).](image)

The small step that continuously improves the working standard is what often is pointed out as the main difference between western and eastern quality management. Working standards within the Kaizen strategy is defined as a set of policies, rules, directives and procedures established by management for all major operations which serves as guidelines that enable all employees to perform their jobs successfully (Imai, 1986). The key to Kaizen is to attain everybody’s involvement. The formalisation of continuous improvements is often demonstrated by the PDCA (Plan, Do, Check, Act), learning cycle and by improvement tools and methods, such as root cause analysis (RCA), (Wilson et al., 1993, Jones et al., 1999, Arnheiter and Maleyeff, 2005), and techniques like cause-and-effect- and tree diagrams.

Learning from experience and improving production is a common strive aiming for customer satisfaction and enhanced efficiency, but the examples for success are scares when it comes to construction industry. (Love et al., 2000) identify TQM as a mean to achieve continuous improvements which is considered to lead construction industry into learning from their mistakes and become a learning organisation. Experiences are exchanged in any company just by talking to and working together, the manner in which this is conducted reflects the company culture. A zero defect strategy is starting to gain attention among industrialised house builders. This strategy addresses the inspections at delivery and aims at lowering the amount of defect notations in the inspection protocols. This is far from the original thought of Zero Defects origin from the work of Philip B. Crosby in the 1960s (Juran and Gryna, 1988). Even if it is a misconception to use the Zero Defect statement in this context, it could be useful to recall the original purpose and maybe even apply it in industrialised housing industry of today. Originally it is a strategy setting a performance standard that can not be misunderstood where every one should perform to the requirements agreed and do it right every time. The quest for standardised solutions could be seen as being in conflict with the tradition of seeking uniqueness in housing fabrication. But lowering the level of defects is not a goal within itself (Deming, 1986) as the customer is looking for continuous improvements regarding performance and style of the product. In order to get quality in the product it is argued by Dahlgaard and Dahlgaard-Park (2006) that the first priority must be to build quality into people. This is to be done in a four step definition of organisational excellence:

1. People
2. Partnership
3. Process of work
4. Products

Implying that the needs of people are prior to the quest for product quality, it is needed to get to one before the other. If people are considered to be internal customers in some form, then the employee, is the way to get to external customers satisfaction. Dahlgaard and Dahlgaard-Park (2006) state that the quality in people has two essential parts: (1) core values, and (2) core competence. The latter is divided into emotional- and intellectual competences. The need for approaching this with top-down and simultaneously bottom-up strategy is emphasised by (Dahlgaard and Dahlgaard-Park, 2006) And supported by Höök and Stehn (2008) emphasising that implementation of bottom up tools will fail if they are not balanced by management towards a cultural change. This is also supported by (Kärnä and Junnonen, 2005). The most critical factor for attaining employee’s motivation and commitment is related to core values,
THEORETICAL FRAMEWORK

which need to be strengthened. Höök (2008) approaches the social context of construction and Lean theories through the theoretical field of organisational culture, emphasising the importance of embedded assumptions, values and practices of organisation members when performing. This approach converges with the statements of social processes in construction (Andersen et al., 2008). This thesis supports the definition of Schein (2004) defining culture as:

…a pattern of shared basic assumptions that has been learnt whilst solving problems, that has worked well enough to be considered valid and, therefore, to be taught to new members as the correct way to perceive, think, and feel in relation to those problems.

This means that best practice exists in every learning organisation, and that it will change as the shared knowledge changes. Schein (2004) states that:

…the key to learning is to get feedback and to take the time to reflect, analyse, and assimilate the implications of what the feedback has communicated.

A learning leader must believe in the power of learning, according to Schein (2004) the learning culture must value reflection and experimentation, by giving time and resources. In this way the learning task will eventually become a shared responsibility. Keys to learning according to Schein (2004) is:

- Feedback
- Time to reflect, analyse, and assimilate.
- Ability to generate new responses.
- Try new ways of doing things and generate feedback from the new behaviour.

This reasoning converges with the work of Senge (2006) who instead works with the learning organisation. The problems with storing knowledge and not activating it is also described by (Mårtensson, 2001). This could be promoted by a change towards a Lean company culture. According to Höök (2008) this is done by understanding and developing practices and working methods at a company level.

2.5 Defects in construction

This section presents a review of defect experience that is documented and reflected over in literature. Early studies have a tendency to blame the occurrence of defects on the craftsmen executing the construction e.g. Schodec (1982) and Moroni and Sartori (1994). This is a view that is eventually complemented with a broadened approach for managing defects regarding its classification, roots, effects and correction. International Council for Research and Innovation in Building and Construction’s (CIB) group W086 were essentially concerned with learning from past and current building pathologies and encouraging the systematic application of that knowledge to the design, construction and management of buildings. Building pathology is defined in CIB (1993) as the systematic treatment of building defects, their causes, consequences and remedies. The same working group define defects a situation where one or more elements don’t perform its intended function and an anomaly is referred to as an indication of a possible defect. This must not be confused with failure, as failure is the termination of ability to perform a required function. This means that a crack in the wall is a defect until the wall fails to perform its structural performance. Building pathology is concerned with defects that lead to extensive failure with not only economical implications but also when there is a danger of structural failure due to defects. This thesis is more concerned with defects that will have an impact on product quality and long term operation and maintenance. Based on an extensive literature review Josephson (1994) categorise conducted defect studies in five groups:
1. Studies Conducted in parallel with the current construction project or as a reconstruction of the construction course.

2. In the form of:
   a. Interviews or questionnaires
   b. Real time observations
   c. Through historical documentation
   d. Through defect database

3. If the study has focused on one or several:
   e. Defects
   f. Projects
   g. Individuals

4. If the study has been continuous on the building site or as occasional visits.

5. If the study has been conducted by individuals active within the project or from external persons.

Josephson decide to work with observers with the sole assignment to document defects during one housing project. These observations were complemented with interviews in order to find root causes to documented defects. The defects in question are all conceived defect during the whole construction phase, building inspection defects are not accounted for. This classification does not however take into consideration the production method used to generate defects. In Love and Josephson (2004) it is stated that the most effective learning in relation to defects takes place in projects when the entire error-recovery process is performed, defined by Sasou and Reason (1999) i.e. detection, indication and correction. It is emphasised that learning is to be encouraged both at individual and organizational level using quality management techniques i.e. root cause analysis, benchmarking, failure effect analysis or Poka-yoke (Shingo, 1986, Wilson et al., 1993). Josephson and Hammarlund (1999) emphasise the importance of gaining knowledge about defects in order to prevent them from arise, this include both cost and causes. The authors suggest that organisational phenomena are the main cause supported by Sasou and Reason (1999), proposing that the root of human error in complex organisations originates in the working team. Pheng and Wee (2001) state that defects arise due to two reasons: nature or human errors, their study is focused on human errors and they present a conceptual framework for defect reduction based on the ISO 9001 model of quality assurance. The authors also present a structure to classify defects in three groups with eleven human-error related causes. Causes of defects accordingly:

1. Technical
   a) Defective materials
   b) Design too difficult to build well
   c) Over emphasis on first cost
   d) Overlooked site conditions
   e) Poor site practice and supervision

2. Management
   a) Defective documentation
   b) Poor communication
   c) Unanticipated consequences of change

3. Human recourse
   a) Ignorance and lack of knowledge
   b) Lack of training and skill
   c) Lack of motivation and care

The ten first groups are originally developed by Porteus (1992) who stated poor communication to be the most common scapegoat among defect work in scientific publications between 1973 and 1983. Porteus suggests a classification system for defects according to origin i.e. type
of natural causes or type of human error. The benefits from this classification are argued to generate feedback information and data for long term learning. The main benefit of this approach is to avoid involvement with issues of blame by using the term negligence in favour of human error and mistakes. This is also promoted by CIB (1993) where it is pointed out the importance of a methodology in order to not just cover the liability aspects but also aspects that can improve quality management systems. Davey et al. (2006) argue that Action Learning will bring contributions and significantly improve defect management and liability regarding defects. A more recent study of defects, performed by Ilozor et al. (2004) argue for an analysis of historical data, which tries to find patterns or sequences in defect occurrence among residential home building in Australia. Based on documented defect inspections from a large amount of houses they find that mistakes regarding framing and roofing are the most prominent areas in need of attention. The literature review conducted by Ilozor et al. (2004) suggests that defect studies are divided between how defects can be systematised, what causes the defect and what fixes or manages the defect. Kim et al. (2007) suggest an Information Communication Technology (ICT) solution for managing defects in large construction projects. They identify three main reasons for inefficient actions regarding defect management:

1. Lack of on-site quality managers.
2. Excessive workload for crews to meet deadlines.
3. Inefficient communication among project participants.

The authors suggest and also carry out a real life test of a computerised Quality Inspection and Defect Management System (QIDMS) using hand held computers, Personal Digital Assistant (PDA) and wireless internet. This enables real time data collection and processing and the study reports significant efficiency improvements based on a ten project study of 700 households in multi storey buildings. The thought of improved efficiency and productivity by intelligent wireless web services is also supported by Aziz et al. (2006). The quality of construction is decisive of building performance both at delivery and after some years of initial occupancy. Chong and Low (2005) investigate the possibility to feed information from operation and maintenance back to design so that future errors could be reduced. The importance of feedback to design is also investigated and emphasised by Scott and Harris (1998) who call for more structured learning on an organisational level. Atkinson (2002) makes a thorough investigation of theories regarding human error and its origin. The author makes interesting conclusions and states that communication has the greatest impact on defect occurrence. Furthermore, it is stated that management is the main factor for performance regarding quality, safety and business, hence the chosen management strategy, promoting communication, will affect also the occurrence of defects. This statement relies on a statement by W. E. Deming that it is the system of work that determines how work is performed and only senior managers can create the system (Deming, 1986).

A contemporary defect study was conducted by Sigfrid (2007) and results are summarised in the report “Defects and deficiencies in new dwellings”. The study was financed by the National Board of Housing, Building and Planning and thus implying its use for generalisation. Defects and deficiencies of six building projects are investigated through interviews and examination of building inspection protocols. All building projects are traditional site constructions, three multi storey projects and three single family houses. Calculations within the study shows that the costs for correcting defects after project delivery in Sweden could be as much as € 1 300 Millions, calculations based on the 2005 years housing production. Lack in the design phase is suggested to contribute together with leadership insufficiencies, motivation and communication. Also the client is to blame for a lack of life cycle approach to the constructed asset. The report continues to state that defects are indications of organisational shortcomings and insufficiencies in the construction industry. Josephson and Saukkoriipi
(2007) summarise waste in Swedish construction projects in four groups and also state the cost of the total project cost:

1. Defects (10 %), costing for hidden and visible defects but also the cost for inspections is classified as waste.
2. Recourses (10 %), efficiency at the construction site.
3. Health and safety (12 %), the largest amount is for rehabilitation and sick pension.
4. System and structure (5 %), there is a clear tendency that efficiency suggestions result in extended support systems.

It is pointed out that improvements should not result in new costly enhanced administration. The authors also call for new vertical management processes i.e. partnering.

2.6 Model of analysis

The theoretical areas presented in this section constitute a framework and are identified in connection to the problem formulation and aim of the thesis outlined in Chapter 1. The theoretical framework is obtained through exploration of the theoretical fields of Lean production, Total Quality Management and Service Life Planning and then complemented with a literature review of studies concerning defects in construction. The theoretical result is a model of analysis to follow for enhanced understanding of how experience feedback can support enhanced product quality in the context of industrialised construction. The model of analysis aims to reflect a quest for balance between production efficiency, product effectiveness and quality in the product see Figure 16.

![Figure 16. Analysis model](image)

Both governmental- and customer demands for enhanced product quality and lowered product- and production cost in construction makes it interesting to investigate how experience feedback can support enhanced product quality. Industrialised housing production is sometimes promoted to possess the means of achieving a new level of production efficiency.
and effectiveness in construction (Apleberger et al., 2007). But both efficiency in production and effectiveness regarding product quality is still to be proven.

This study investigates the case of timber framed volume prefabrication as one form of industrialised housing from a threefold theoretical framework constituting: (1) Production efficiency and company profit theories from a Lean perspective, (2) product effectiveness and customer quality through a Total Quality Management perspective, and (3) product life cycle approach through theories of Service Life Planning, see Figure 16. This is complemented with knowledge about defects in construction, as defects are one prominent and important part of the experience feedback information. From a Lean perspective defects are seen as one of the seven wastes in production (Liker, 2004) resulting in lowered long term profit. From a quality management perspective defects are signs of lowered product quality and must be detected in order not to reach the customer (Feigenbaum, 1991).

Quality management theories are developed to support customer focus in manufacturing of products, both service and goods and Lean concept is developed in manufacturing environments i.e. car production as a means to enhance profit, as industrialised housing is part of both manufacturing and construction also the Lean construction concept is included in the framework. To support the performance based building regulations, new ISO standards for Service Life Planning are developed, to aid in the quest for enhanced product quality and to gain control of operation and maintenance costs that leads to enhanced product effectiveness.
3 Method

This chapter includes the research method and a description of data collection methods. The first sections describe how paper I-IV is related to case studies, theory and thesis, followed by pointing out how papers and investigated audits are related to the production process. Then the following sections accounts for what has been done in each paper in connection to the three areas of Service Life Planning, feedback information and feedback information analysis.

3.1 Research method

The research within this thesis tries to answer the questions of why feedback is essential, how feedback is utilised and how it can be further implemented to enhance product quality. According to e.g. Yin (2003) why and how questions are best answered using exploratory case study techniques. The case study format allows for a large variety of data collection methods (Fellows and Liu, 2003) and is suitable for attempts to derive general conclusions from a limited number of cases (Gummesson, 2000). By using both qualitative and quantitative research methods and triangulation, the validation of the cases are validated (Yin, 2003). Figure 17 illustrates how paper I, II, III and IV corresponds to the case studies conducted.

Figure 17. Case studies in relation to paper and thesis.

Quality improvement through feedback is essential in the design stage and when initiating a product development. This is investigated in the first paper (Meiling and Johnsson, 2007) through studying the development of a staircase. Paper II-IV focuses on experience feedback through the study of defects which are detected at three control points in the building process, see Figure 18. Audits to detect anomalies in the production process are part of a current state. They represent low hanging fruit when it comes to finding feedback information. In Sweden, it is mandatory to perform a final audit when the building is complete and a warranty audit after the building has been in service for two years. Both audits are made by external professionals. In addition, the studied companies have an internal quality audit before the manufactured timber framed volume modules leave the factory, see Figure 18.
3.2 Application of Service Life Planning

A case study was conducted from September 2006 to January 2007, presented in paper I (Meiling and Johnsson, 2007), aiming to explore the quality enhancement process through an application of Service Life Planning regarding the development of a wooden staircase for multi-storey buildings. The choice of case was made in a focus group meeting consisting of one representative from each of the four companies in Table 6. The strategy was chosen to utilise group member interaction to get a broader base for case study decision (Wibeck, 2000). The selection of a single development project was based on the assumption that all companies have similar production process. Wooden stairs represent a major challenge in product development for the companies as it comprises functional requirements regarding technique, economy, aesthetics and production. Therefore single case study was considered to be significant regarding evaluation of the use of feedback in the quality enhancement process. A stairwell is defined as the enclosure of a stairway, or the space around which a stair is disposed (ISO 6707-1, 4.4.15). Within the timber framed volume production system the prefabricated stairwell volume is produced in parallel to the apartment volumes.

Semi structured interviews was conducted, in order to enable probing of responses (Fellows and Liu, 2003), with both a stair supplier, and a timber framed volume manufacturer, company B, together with 2 focus group meetings with the head of sales and construction from both companies. The common market was scanned for flooring materials that could be considered possible to utilise on the steps and requirements were specified from stair production, house manufacturing, authorities and clients. An attempt was made to apply Service Life Planning through the ISO 15686-1 standard methodology. This was chosen as the ISO standard methodology relies on feedback information and comprises the entire life cycle of the product.
In addition this study was complemented with quality audits among existing, in use, wooden stairwell populations.

As an extension of the first study (Meiling and Johnsson, 2007) a quantitative study on people’s experience of wooden stairs was initiated. This study is presented in section 4.1.1. Case company A was chosen for this study as they possessed a large population of wooden stairs. From February to September 2007 stairwells of 13 different multi storey living blocks (Appendix 4) was examined by the author in-situ regarding abrasion and quality status and 707 questionnaires (Appendix 1) were distributed within the 13 blocks. Questionnaires were chosen to gain as much information as possible at a low cost, as it was unclear how design could meet requirements from customers to the building clients i.e. the tenants. As a complement to the questionnaire and in-situ examination 13 semi-structured interviews (Appendix 3) were conducted with house janitors in the buildings. This was done in an attempt to triangulate the results (Fellows and Liu, 2003) results were compared and analysed with spreadsheets and diagrams comparing mean values and sums, a cause and effect analysis was conducted. The questionnaire was designed to gain as much knowledge as possible about the end users experiences and thoughts of wooden stairs and contained both closed and open questions. A total of 205 answers from 722 distributed questionnaires, gives 28% answering frequency. Distributed questionnaires were obtained by placing a labelled collecting box in the staircase entrance in all the investigated stairwells. These boxes were emptied after a period of one week. The building population was chosen in case company A’s prime market: out of the 13 investigated blocks 6 was from case company A containing wooden stairs. Furthermore 2 blocks were chosen from another prefabrication strategy, massive timber elements, but with timber stairs from the same supplier as for company A. An additional 2 blocks equipped with concrete stairs was chosen as reference, in order to compare the abrasion. The blocks with concrete stairs were one from case company B and one external company utilising steel framed volume prefabrication. All houses were 4 to 8 story buildings produced with prefabricated volumes.

### 3.3 Feedback information

The aim of this study was to understand the industrialised production process regarding feedback and to identify and explore existing information, ready to transform into feedback data. It is presented in paper II (Meiling and Johnson, 2008a) and paper III (Meiling and Johnson, 2008b). The data collection methods chosen are both qualitative and quantitative. A multiple case study was chosen as the overall method in order to achieve a wider relevance. Qualitative interviews were conducted, with multiple respondents to gain validity, answering how feedback is utilised and what the implications could be. Empirical results are based on data gathered through interviews and observations from October 2007 to February 2008. The multiple case study involved four companies A-D, see Table 6. The manufacturing process was described and probed through semi structured interviews to document the feedback management regarding the technical solutions utilised as well as the overall quality in the product. A quantitative study was conducted through simple statistical analysis (using spreadsheets, calculating mean value and standard deviation) of defects, found in quality audits, see Figure 18, answering how many defects are at hand.

In order to document and understand the on-site assembly of volumes five field trips to building sites were conducted. Semi-structured, in-depth interviews were performed with the quality manager at one company, two site managers at one company, the sales manager at two companies and two production managers at one company. Building audits from 16 building projects were examined representing 958 prefabricated timber framed volume modules. A total of 2,829 defects were sorted by their origin. To evaluate the possibility of using existing audits, a population representing 20% of the total production, from 1994 to 2007, was explored.
Also, warranty audits from 9 projects were examined, representing 909 modules and 490 defects.

Table 7. Number of audits per company.

<table>
<thead>
<tr>
<th>Company</th>
<th>Projects(no.)</th>
<th>Defects(no.)</th>
<th>Modules(no.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building audits</td>
<td>A 5</td>
<td>414</td>
<td>81</td>
</tr>
<tr>
<td></td>
<td>B 11</td>
<td>2415</td>
<td>877</td>
</tr>
<tr>
<td>Warranty audits</td>
<td>A 5</td>
<td>66</td>
<td>81</td>
</tr>
<tr>
<td></td>
<td>B 4</td>
<td>424</td>
<td>828</td>
</tr>
</tbody>
</table>

Building and warranty audits, compulsory through contract in Sweden, are regulated and formalised through a non-profit association of actors in the construction industry. A rigorous set of rules are presented in two regulations; general regulations for construction, AB04 (AB, 2004), and design build contracts, ABT94 (ABT, 1994).

3.4 Feedback information analysis

This study is presented in paper IV (Johnsson and Meiling, 2008), and was conducted from July to September 2008. The aim was to characterise defects in industrialised housing and compare the findings to earlier studies concerning on-site construction, thus revealing the current quality level of industrialised construction. Every defect was coded and entered in SPSS statistical software for analysis. The main interest was to quantify data in each coded group to be able to characterise the defects. The only qualitative work conducted was the sorting of defects through coding into 6 different groups before analysis, see Table 8.

Table 8. Nominal scales for characterising defects.

<table>
<thead>
<tr>
<th>Where does the defect occur?</th>
<th>What is defect?</th>
<th>What type of defect occurs?</th>
<th>What measures were taken to correct the defect?</th>
<th>Why did the defect occur (root cause)?</th>
<th>When did the defect occur?</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 Unrelated</td>
<td>0 Unrelated</td>
<td>0 Unrelated</td>
<td>0 Unrelated</td>
<td>0 Unrelated</td>
<td>0 Unrelated</td>
</tr>
<tr>
<td>1 Dwelling</td>
<td>1 Int. installations</td>
<td>1 Missing</td>
<td>1 None</td>
<td>1 Transport</td>
<td>1 Structural design</td>
</tr>
<tr>
<td>2 Common areas</td>
<td>2 HVAC</td>
<td>2 Unfinished</td>
<td>2 Cleaning</td>
<td>2 Damaged</td>
<td>2 Factory</td>
</tr>
<tr>
<td>3 Separate buildings</td>
<td>3 Broken</td>
<td>3 Adjustment</td>
<td>3 Bad craftsmanship</td>
<td>3 Bad craftsmanship</td>
<td>3 Factory</td>
</tr>
<tr>
<td>4 Outdoors</td>
<td>4 Erroneous</td>
<td>4 Completion</td>
<td>4 Completion</td>
<td>4 Structural error</td>
<td>4 Assembly</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5 Repair</td>
<td></td>
<td></td>
<td>5 Warranty time</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6 Exchange</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The first two categories in Table 8, where and when had a sub-category with more detailed coding, which is presented in Table 11 and Table 9.
Table 9. Sub categories for the Where category in Table 8.

<table>
<thead>
<tr>
<th>Where;</th>
<th>Where;</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 Common areas</td>
<td>3 Separate buildings</td>
</tr>
<tr>
<td>1 Waste disposal</td>
<td>1 Waste disposal</td>
</tr>
<tr>
<td>2 Laundry</td>
<td>2 Laundry</td>
</tr>
<tr>
<td>3 Storeroom</td>
<td>3 Storeroom</td>
</tr>
<tr>
<td>4 Ventilation</td>
<td></td>
</tr>
<tr>
<td>5 Electricity</td>
<td></td>
</tr>
<tr>
<td>6 Cleaning</td>
<td></td>
</tr>
<tr>
<td>7 Entrance</td>
<td></td>
</tr>
<tr>
<td>8 Stairwell</td>
<td></td>
</tr>
<tr>
<td>9 Corridor</td>
<td></td>
</tr>
</tbody>
</table>

Table 10. Sub categories for the What category in Table 8.

<table>
<thead>
<tr>
<th>What</th>
<th>What</th>
<th>What</th>
<th>What</th>
<th>What</th>
<th>What</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Int. installations</td>
<td>1 Radiator</td>
<td>1 Windows</td>
<td>1 Tiles</td>
<td>1 Clinker</td>
<td>1 Balcony</td>
</tr>
<tr>
<td>2 Bathroom</td>
<td>2 Pipes</td>
<td>2 Doors</td>
<td>2 Wallpaper</td>
<td>2 Carpet</td>
<td>2 Oriel</td>
</tr>
<tr>
<td>3 Room</td>
<td>3 Electricity</td>
<td>3 Openings</td>
<td>3 Painting</td>
<td>3 Parquet</td>
<td></td>
</tr>
<tr>
<td>4 Linings</td>
<td>4 Linings</td>
<td>4 Linings</td>
<td>4 Linings</td>
<td>4 Linings</td>
<td>4 Linings</td>
</tr>
<tr>
<td>5 Threshold</td>
<td>5 Threshold</td>
<td>5 Threshold</td>
<td>5 Threshold</td>
<td>5 Threshold</td>
<td>5 Threshold</td>
</tr>
</tbody>
</table>

To establish an overview over the type of defects, when they occur and what causes them, audits from the three control points: factory, building and warranty where gathered. A handful of projects from company A and B where complete data existed (factory, final and warranty audit) were selected, and Table 10.

Table 11. Characteristics of case company and selected projects.

<table>
<thead>
<tr>
<th>Case Company</th>
<th>No of employees</th>
<th>Main products</th>
<th>Turnover (MEuro)</th>
<th>Selected projects (no. of volume modules)</th>
<th>No. of storeys</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>A 150</td>
<td>Multi family and student dwellings</td>
<td>34</td>
<td>Condominiums (40 mod.)</td>
<td>2</td>
<td>2004</td>
<td></td>
</tr>
<tr>
<td>B 253</td>
<td>Schools and office buildings</td>
<td>43</td>
<td>School (11mod.)</td>
<td>1</td>
<td>2006</td>
<td></td>
</tr>
</tbody>
</table>

443 volume modules were included in the analysis of the quality audits. The total of defects across all projects adds up to 1234 defects in the factory audits, 1147 defects in the final audits and 332 defects in the warranty audits, a grand total of 2713. Defects are recorded in reports (the result of a quality audit) and stored in text format at the companies. The reports were reviewed and all defects coded using six different categories; where, what, type, measure, why and when. Each category was associated with a nominal scale according to Table 8.
4 RESULT AND ANALYSIS

This chapter presents the main findings from the appended papers and the complementary study presented in section 4.1.1

4.1 Application of Service Life Planning

Paper I (Meiling and Johnsson, 2007) presents a quality improvement case study where an attempt to apply Service Life Planning regarding product development of a timber stairwell for multi storey buildings was conducted. The stairwell represents important functions from a technical, economical and aesthetic viewpoint. The design has to consider resistance to wear, cleaning and vandalism, bearing resistance, fire safety but also conform to demands of industrialised housing production. Thus demands exist on the levels of material, component and building constituting a complex matrix of requirements. Wooden stairs are not manufactured in-house by the timber framed volume producer, but purchased through a supplier specialising in this product. Diverse types of commercially available timber are used to build steps, but the staircases must always fulfil safety, durability and appearance requirements. Notably, the surface of the steps must be resistant to “wear” under highly abrasive conditions. Interviews with both a stair supplier and a timber volume element manufacturer, have revealed the following advantages and concerns, references are available in paper I (Meiling and Johnsson, 2007):

- Wooden stairs are more practical than other alternatives due to their workability and ease of assembly in a factory.
- There is a lack of maintenance strategy for stairwells, resulting in concerns regarding: quality, choice of surface/cladding, long-term appearance of the stringer, i.e. the inclined part supporting the steps.
- Lack of aesthetically pleasing, highly abrasion-resistant, surface choices, e.g. customers often request stone cladding
- The ambition is to procure a staircase that needs no complementary work.
- Moisture damage is not acceptable in the connections between components in the stair.
- There is not, as yet, a satisfactory solution to the problem of “nosing” at the front of the steps.
- Existing staircases have not yet been optimized with respect to fire safety. There is a need for more economical fire-protected staircases
- There are problems in communicating the sizes of stairwells, which sometimes result in insufficient space for prefabricated staircases.

The identification of possible flooring materials was chosen as a first phase of this investigation, Table 12, with an aim to investigate if the requirements for stairs are possible to comply, Table 13. The list of preliminary requirements was put together in cooperation between the stair and housing company.
RESULT AND ANALYSIS

Table 12. List of flooring materials.

<table>
<thead>
<tr>
<th>Flooring materials</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. linoleum (resilient)</td>
<td>1. Abrasion resistance</td>
</tr>
<tr>
<td>2. vinyl (resilient)</td>
<td>2. Moisture/water resistance</td>
</tr>
<tr>
<td>3. rubber (resilient)</td>
<td>3. Temperature resistance</td>
</tr>
<tr>
<td>4. cork (resilient)</td>
<td>4. Impact resistance</td>
</tr>
<tr>
<td>5. laminate (hpl)</td>
<td>5. Fire resistance</td>
</tr>
<tr>
<td>6. stone</td>
<td>6. Low slip</td>
</tr>
<tr>
<td>7. concrete, terrazzo</td>
<td>7. Resistance to chemicals</td>
</tr>
<tr>
<td>8. ceramic tile</td>
<td>8. Replaceable</td>
</tr>
<tr>
<td>9. wood and parquet</td>
<td>9. Workability</td>
</tr>
<tr>
<td>10. resin flooring</td>
<td>10. Compatible with nosing</td>
</tr>
<tr>
<td>11. carpet</td>
<td>11. Compatible with string</td>
</tr>
</tbody>
</table>

After the study of different flooring materials listed above the materials were preliminary sorted by comparison to the requirement list, four materials were chosen for further investigation. These were: (1) Resin floor (Peran STB classic by Flowcrete), (2) Composite material with PVC and minerals (LifeLine by Upofloor Oy), (3) PVC (Stair treads by Flexco), and (4) High pressure laminate (HPL).

Each material is managed by a unique standard, where e.g. resistance to abrasion is measured without possibility to make performance based comparisons. A weighting criteria matrix was used (Johannesson et al., 2004), a technique where requirements are ranked and compared to each material, the high pressure laminate was chosen for further investigation. The laminate products are classified in the standard SS-EN 438 (part 3 to 6). A detailed requirement list was established, see Table 14.

Table 13. List of preliminary requirements.

Table 14. List of detailed requirements.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Abrasion resistance</td>
<td>Class AC5, IP-value ≥ 6000 according SS EN13329</td>
</tr>
<tr>
<td>2. Moisture/water resistance</td>
<td>100 % RH, wet cleaning</td>
</tr>
<tr>
<td>3. Temperature resistance</td>
<td>0-180 ºC</td>
</tr>
<tr>
<td>4. Impact resistance</td>
<td>Class: IC3 according to SS EN13329</td>
</tr>
<tr>
<td>5. Fire resistance</td>
<td>At least Cfl -S1 according to BBR 5:512, for floor, reaction to fire</td>
</tr>
<tr>
<td>6. Low slip</td>
<td>Coefficient of dynamic frictions (µ) according to; SS-EN 13893, or a value &gt;35 according the pendulum test</td>
</tr>
<tr>
<td>7. Resistance to chemicals</td>
<td>Detergent, solvent</td>
</tr>
<tr>
<td>8. Replaceable</td>
<td>Maintenance, operation</td>
</tr>
<tr>
<td>9. Workability</td>
<td>With mill, cutter, saw, drill and so on.</td>
</tr>
<tr>
<td>10. Compatible with nosing</td>
<td>In the fabrication process</td>
</tr>
<tr>
<td>11. Compatible with string</td>
<td>Covering of the string</td>
</tr>
<tr>
<td>12. Able to be glued</td>
<td>On wood</td>
</tr>
<tr>
<td>13. Environmentally friendly</td>
<td>VOC test according the final draft pr EN 15052: 2006</td>
</tr>
<tr>
<td>14. Reasonably priced</td>
<td>Up to fabricant</td>
</tr>
</tbody>
</table>

A test stair was produced with high pressure laminate ready for evaluation. A draft for testing and evaluation was produced. The short time test should consist of a laboratory scale test applied
to samples made of laminate materials, glued on wooden edge-glued panel substrate. The goals are to evaluate the specific properties of the laminate material and see the interaction with the wooden substrate. The tests are:

- Abrasion test
- Slippery test
- Impact test
- Resistance to a climate shock

The long time test should be a full scale test. The test stair should be placed in an existing building where it will be used in real life conditions. The goal of this test is to evaluate some properties for which there are no standard test methods for testing. These are:

- Material workability with CNC machine
- Performance of the seams and joints between the laminate and supporting material
- Glue line (adhesion on the substrate)
- Wear and scratches
- General appearance

The actual testing has been drafted, but was not conducted within this thesis. Instead an overall evaluation was performed revealing the following (Meiling and Johnsson, 2007):

- The house producer desires to purchase standardised staircases, while the staircase manufacturer handles their production as custom-made, hence there is an information gap, resulting in low fulfilment of functional requirements and high expenditure.

- A missing function regarding feedback and product development within the case company.

- The framework of the method described in the ISO standard for Service Life Planning is applicable to the development of wood products, but also that a receiving mechanism within the timber framed volume companies is lacking today.

- Difficulties when requirements are to be communicated across the material, component and building level, e.g. material standards for flooring materials are not compatible for making cross examinations of different design solutions.

- Knowledge of both the performance requirements and likely performance over time of products under development is essential for reliable forecasts of their service lives.

- Lack of appropriate management structures is hindering the quality assurance of the product development. I.e. there is no management decision of quality focus and no allocated resources.

- Lack of available data for executing Service Life Planning through the ISO standard.

- The obstacles to applying knowledge from the car industry are less formidable in the investigated companies than in ordinary construction companies.

In order to effectively handle the demands for new products with enhanced quality, the timber framed volume housing producer needs to separate the product development process from the ordinary production process. If not, the control of the process is lost and there is no receiving structure for the Service Life Planning method, leaving it up to the people in the company to remember it, rather than having a structure to support it. A performance based development would benefit from communication of requirements across the system levels i.e. material,
component and building level. From paper I (Meiling and Johnsson, 2007) it is clear that further information is needed in order to succeed with product development of staircases. No experience feedback information is available, for Service Life Planning, at the case study companies regarding multi-storey housing timber staircases, even if these stairs have been utilised since 1994. In order to demonstrate a methodology, for generating feedback, new information was gathered through a questionnaire (Appendix 1), on-site inspections (Appendix 2) and interviews (interview protocol Appendix 3) described in section 4.1.1 complementary study.

4.1.1 Complementary study

The results from the questionnaires are both quantitative and qualitative, they reveal what attributes are most appreciated regarding stairwells, regardless of material but also how different staircase materials and designs are perceived by tenants and janitors, Table 15. From the six attributes, in Table 15, (4) sound, (2) function (sideway space and transportation) are the most appreciated among tenants.

Table 15. Attributes revealed from questionnaire to tenants.

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Safety</td>
<td>The stairwell should be safe to visit</td>
</tr>
<tr>
<td>2. Function</td>
<td>It is appreciated if it is easy to walk, meet, and move e.g. furnisher, the stairwell should be wide, airy and bright.</td>
</tr>
<tr>
<td>3. Condition</td>
<td>The stairwell should stay fit over time, designed in order to be easy to clean and maintain</td>
</tr>
<tr>
<td>4. Sound</td>
<td>There should be minimal sound transfer to apartments</td>
</tr>
<tr>
<td>5. Light</td>
<td>Colours should be bright and the illumination should be good in combination with openings for daylight</td>
</tr>
<tr>
<td>6. Inviting</td>
<td>Maintenance should be a priority making the stairwell inviting</td>
</tr>
</tbody>
</table>

The six attributes in Table 15 were gathered through an open question of what the tenant personally thought represented a good stairwell. When asked to choose from a preset of 21 attributes the same six attributes scored the highest level; very important. The least important attribute was to have a balcony in the stairwell. Results from the questionnaire reveals that wooden stairs are well perceived by more than half (51 %) of the tenants living with wooden stairs. The score for tenants living with concrete stairs was (41 %). When there is no closed stairwell the tenants feel it is too noisy in the apartment, regardless of material. When seeking a preferred design, a grand total of 67 % prefer staircase design A from Figure 19.

![Figure 19. Staircases to choose from in the questionnaire.](image)

When asked what notion was most prominent when entering the stairwell of their own, the most positive reactions was given to: tile flooring, light colours, and large windows. 89 % of the tenants feel safe in their stairwell. The ones not feeling safe blame e.g. wet floor, moving stair, and a fragile design. When asked about the flooring material linoleum was bottom ranked
and tiles were top ranked. A wide stair is more preferable; the investigated stairs had a span of 700 mm to 1150 mm, and the widest stair had the most satisfied tenants.

The interviews with 13 janitors revealed that the stairs should be clean and empty from hindrances. Concrete and stone materials are preferred materials from a maintenance perspective. After documenting each stair making individual grading, using a five grade scale from very bad to very good (Appendix 2), a causes and effects of abrasion was analysed using a cause-and-effect diagram, see Figure 20. This was possible as the input for this analysis was gathered through real life examination of staircases.

Figure 20. Cause and effect diagram for reasons of abrasion in the staircase.

To summarise why wooden stairs are perceived as being worn, the following issues arise:

- Inner and outer string: Abrasion, stains and marks are recurrent for all the wooden stairs. This is from every day cleaning, walking and moving things.

- Abrasion materials on strings: When linoleum, wood and rubber materials are chosen it is quickly worn through marks, stains and shifting colours. Stone and plastic materials are preferable.

- The wooden stairs are clumsy compared to steel design in the same shape. The aluminium nosing used on every step collects dirt. Handrails should be designed to enable smooth movement without interruptions, one rail is better than a divided.

- A lack of maintenance strategy exposes the staircase to ad hoc cleaning and maintenance practices. The stair is affected also by effect of supporting functions such as storing of bicycles, baby carriages etc.

The three most appreciated stairs and stairwells according to the questionnaire and the on-site inspection are presented in Figure 21.
The results constitutes a specific, easy to communicate, enhancement list for more abrasion resistant wooden stairs leading to potentially more satisfied tenants and customers. The recommendations regarding stairs is summarised as:

- Use the overall requirements that are formulated by the National Board of Housing, Building and Planning.
- Make the stairs a minimum of 1.20 meter; this is the minimum for transporting a stretcher.
- Use homogenous plastic tile or other resistant material for the flooring material.
- Use stair design A, Figure 19.
- Use abrasion resistant materials for stringers that are exposed to wear.
- Make the handrail in one smote piece.
- Avoid sharp edges and clumsy design as it wears quickly.
- Avoid aluminium nosing.
- Rethink installation as movements have been detected at several stairs.

As a result of the feedback initiatives conducted a new enhanced staircase has been developed by the stair producer and presented to the housing company for acceptance with new design according to recommendations. Service Life Planning was not successfully conducted within this project. Questionnaires for tenants and structured interview document for janitors, chosen objects for inspection and inspection results are appended, Appendix 1-4.

4.2 Feedback information

This section summarises results from two papers. Paper II (Meiling and Johnsson, 2008a) outlines the production process, identify feedback opportunities and in paper III (Meiling and Johnsson, 2008b) a defect analysis is initiated. The four companies investigated show similar patterns regarding feedback and learning behaviour. Information and knowledge is dependent on individuals and data is organised with building projects as a base as already found in paper I and thus reconfirmed. This is effective while the project is current but difficult when trying to reuse experiences after project closure also found in paper I and confirmed in II and III. The timber volume element house manufacturer, rather than builder, is often responsible for both design and production, giving the opportunity of seeking and promoting early design decisions compatible with production capability. This is imperative to attain a cost effective product, and
demonstrates the contradiction between manufacturing and construction. When manufacturing prefabricated volumes, the number of participating companies is less, resulting in enhanced possibilities concerning learning from experience, e.g. feedback, and thus finding connections to improvement possibilities within the company. This in turn could present a competitive edge towards other building systems and promote long-term quality. This is effective while the project is current but difficult when trying to reuse experiences after project closure also found in paper I and confirmed in II and III.

It is found that feedback initiatives exist but not on a continuous basis, more ad hoc and dependent on individual initiatives. Below are some examples of semi discrete initiatives, representing feedback initiatives, meaning they happened more than once (Meiling and Johnson, 2008a, Meiling and Johnson, 2008b):

- Meetings, with staff from design, prefabrication and assembly where discussions have been documented in the intention of further feedback analysis.
- Appointed groups, representing assembly, for contributing feedback and reporting on new solutions back to production.
- Qualitative debriefing documents filed with project.
- Quality audits are performed in the factory before transportation.

But no person deals with the incoming information from these initiatives, in a consistent manor, and transforming it to engineering knowledge and changing the platform – the building system or even the production process. The various results from these initiatives are not analysed in a sustainable manner where the goal is continuous improvements, or for further implementation in production. Three different quality audits are being executed in the companies, one in production (internal) before transport to building site, one after finishing the building on site and the third after two year warranty time, see Figure 22, these audits are documented and stored both in binders, in piles and in computer files.

![Figure 22. Defects from three different audits investigated in the study.](image-url)

The three audits are identified as a bearer of existing information. There is no attempt among the companies to analyse these audits. Two companies were chosen when analysing data from final and warranty audits (Meiling and Johnson, 2008b). Within the audits only indoor building protocols were chosen, based on earlier studies from Sigfrid (2007), Persson (2006), and Josephson and Hammarlund (1999), see Table 16.
### Table 16. Summary of inspection protocols

<table>
<thead>
<tr>
<th>Company</th>
<th>Projects (no.)</th>
<th>Defects (no.)</th>
<th>Modules (no.)</th>
<th>Mean value (Def./Mod.)</th>
<th>Std. dev. (%)</th>
<th>Max/min (Defects)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final audits A</td>
<td>5</td>
<td>414</td>
<td>81</td>
<td>6.1</td>
<td>66</td>
<td>1/11</td>
</tr>
<tr>
<td>B</td>
<td>11</td>
<td>2415</td>
<td>877</td>
<td>3.1</td>
<td>63</td>
<td>1/7</td>
</tr>
<tr>
<td>Warranty audits A</td>
<td>5</td>
<td>66</td>
<td>81</td>
<td>1.1</td>
<td>81</td>
<td>0.4/2.4</td>
</tr>
<tr>
<td>B</td>
<td>4</td>
<td>424</td>
<td>828</td>
<td>0.9</td>
<td>70</td>
<td>0.3/1.6</td>
</tr>
</tbody>
</table>

From Table 16 it is concluded that the standard deviation is large, implying uneven quality in each project. Analysing data was connected to two difficulties. Firstly in transforming the qualitative remarks to data, and secondly by translating each individually made defect remark. As design, production and assembly is organised within the same company there is a natural link for communication that is not utilised. Information is stuck in the system piling up at two bottlenecks, one regarding the transformation of existing information and the other as a non-existent resource for product development. The results in paper I, II and III points to missing strategy for communication regarding feedback between design, factory and on site assembly. When focusing on defects in a Lean context the product development is as imperative as manufacturing, supply and distribution – findings imply product development is the missing link for feedback to function at the case study companies.

#### 4.3 Feedback information analysis

Paper IV (Johnsson and Meiling, 2008) makes further analysis of the data found in paper II-III. The results show that industrialised housing is neither better nor worse in terms of product quality, when analysing defects found in quality audits. The organisation at the companies offers great possibilities for experience feedback, but this is not functioning currently. When analysing sorted defects from final and warranty audits it is clear that dwellings harness the most defects, which is not surprising since they constitute the major parts of the buildings. The higher proportion of defects in common areas recorded in the final audits (which can be seen in Figure 23) is also no surprise since common areas are constructed during onsite work, and thus their frequency will inevitably rise in the final audits.

![Figure 23. Where do defects occur.](image)

The most frequent problems were clearly associated with walls and openings. Recorded defects include holes and mess on the walls caused by craftsmen, missing linings around doors and windows, and doors in need of adjustment due to movements in the structure. Of the grand total, 33 % of all defects were related to walls, and 52 % to walls or openings. Defects in interior installations emerged in the factory and final audits, and concerned objects that were missing or not properly installed. From the investigated final audits, almost half of the defects originate from factory production, followed by 35 % from assembly activities. The type of
defect is directly coupled to the cost to correct it; therefore it is interesting to grade the severity of the defect, Figure 24.

Figure 24. Types of defects.

Figure 24 shows that many items were missing before delivery at the time of the factory audits (518 items in total, equivalent to 1.2 items missing/volume module, accounting for 42 % of the defects recorded in these audits). Furthermore, many defects recorded in the factory audits concerned broken items (35 %) that had to be corrected before the final audit. In the final audits, the lion’s share of defects concerned things that had not been delivered according to the contract (55 %). On average, 79 items/project were listed as not to the customer’s satisfaction in the final audits. According to the warranty audits, some 20 items/project did not meet contract stipulations. To qualitatively assess the costs of the defects for the contractor and establish another measure of the costs of correcting them, the measures taken to correct each defect were recorded. Most of the defects (51 % of the total) were small, requiring only minor adjustments. Typical defects included stains, mess, small cracks and marks. The numbers of defects requiring repair or exchange amounted to 9.6 % (260/2713) of the total. In the factory audits completion was the second most common measure to correct defects, which is unsurprising since many items were missing in that phase.

During factory production, most structural errors are directly connected to design errors, and long-term effects on the building system only become apparent after some time in service. Typical structural errors recorded in the warranty audits included cracks in corners and movements in the structure. Structural errors constituted nearly half of all the defects listed in the warranty audits, corresponding to 6 % of the grand total. For industrialised housing it is interesting to examine the number of defects associated with structural errors, since the structure is repeated, so structural errors affect every volume module produced. Such errors constituted 21 % (578/2713) of the defects. During factory production, most structural errors are directly connected to design errors, and long-term effects on the building system only become apparent after some time in service. Typical structural errors recorded in the warranty audits included cracks in corners and movements in the structure.

Almost half of the defects recorded in the investigated final audits originated during the factory production processes, followed by 35 % from assembly activities. Production in the factory is intense, and this is where attempts to optimise the work have primarily focused. Relatively little attention has been paid to the assembly phase, but this should be worthwhile, especially for company B, since many defects pertain to installations handled in the assembly phase.
5 DISCUSSION

This chapter highlights the results from papers I-IV, using the model of analysis presented in Chapter 2. The first section makes an attempt to pinpoint a perceived balance between production efficiency, product effectiveness and customer value. The following section continues by discussing application of Service Life Planning. The last section discusses the benefits and implications of experience feedback in construction.

5.1 Product effectiveness and production efficiency

Because industrialised housing companies strive to control a large part of the construction process, i.e. briefing, design, production and assembly, they have the possibility to offer a more defined product. The product offer exposes the company name and brand to market forces. The company exposes their company name, since it is intended to reflect product quality towards the customer, and a defect product influences the notion of other products within the company (Bergman and Klefsjö, 2003). This forces industrialised housing to achieve a higher level of quality than traditional construction, which is a challenge since these companies are only in the first of four phases of quality development, namely the phase of quality inspection, and need to rise to the third level, quality assurance, to implement continuous improvements (Bergman and Klefsjö, 2003; Juran and Gryna, 1988; Dale, 1999).

Through the ISO 9000 series, authorities suggest a tool for enhanced quality, but only by having knowledge about the standard and not actually implementing it (BFS, 1996). The present action is only on the output of production, when the product is already made. The third level of quality commitment requires these companies to take action regarding design of both product and process (Bergman and Klefsjö, 2003, Juran and Gryna, 1988). But legislation and customer weakness seem to allow only the lowest possible level of quality commitment in construction (Josephson and Saukkoriipi, 2007). So far, quality work in construction is conducted to gain client confidence rather enhanced product quality or improved production flow (Landin, 2000, Meiling and Johnsonson, 2008b). But the demands for enhanced quality and efficiency from authorities and clients imply that quality management should be a means of gaining more satisfied customers, meaning enhanced effectiveness. The benefits of industrialised housing cannot be achieved by focusing solely on external customer value, while suppressing internal production efficiency and forgetting internal customers.

By choosing and implementing a quality management system, a company’s management expresses a wish to reduce uncertainties and minimise defects and thus improve product quality. This represents, for example, a focus to minimise poor quality costs, i.e. if production could be managed towards zero defects the system would be optimal. But people do make mistakes (Juran and Gryna, 1993, Josephson and Saukkoriipi, 2007). In this sense, Lean supports a development where the current state gradually evolves into a future state with enhanced perfection and the elimination of non-value adding activities, and not only by lowering the poor quality costs. This is done by the systematic exposure of problems in a standardised environment (Höök, 2008, Womack and Jones, 2003). This thesis does not suggest choosing between Lean and TQM, but rather recognise how companies have the position of mastering both concepts. If the theoretical framework for Lean production/construction can support the efficient production of multi storey houses, Total Quality Management could be perceived as a method of achieving effectiveness. Koskela (1992) does not support this, and instead proposes a choice to be made.

If the development of product quality in the housing industry is to be conducted through the people working in a company, the defects signal a need for learning in the organisation rather than a technical, economical problem. The most alarming effect of defects is not the cost of correcting them, but the resulting decreased product quality. The two main reasons for
investigating defects are to lower poor quality costs and improve product quality and customer satisfaction. This state has not yet been reached in industrialised multi-storey housing in Sweden. Instead, there is a focus on technical problems and logistics in projects, implying that innovation and process behaviour suffer. According to Liker (2004), people continuously solving root problems drives learning, which in turn leads to enhanced quality. Andersen et al. (2008) emphasise the importance of understanding and managing the social infrastructure versus company culture. The investigated companies are well aware of how Lean tools have been proven to eliminate waste and gain flow in production. Some have adopted a tool-based approach towards Lean. Yet, there is no spoken intent for implementing a Lean strategy.

5.2 Quality improvement through Service Life Planning

As timber framed volume producers strive to control their product, their demand towards their suppliers increases. The housing producer in this case study is developing from a regular building firm with in-house production to an industry where quality inspection should turn into quality control. This development increases the possibilities to also incorporate Service Life Planning, a method that relies on well-defined materials, components and products, as seen in the case study. Of course, there is a strong incentive for Service Life Planning when customers declare a lack of trust in the product offered (Höök, 2005).

There are five hindrances in applying quality management in construction, as listed in the ISO user guide (Jernberg, 2005), viz. (1) Complexity, (2) Knowledge of service life (last for a long time), (3) Environmental considerations, (4) Uniformity of Product and (5) Uniformity of Production. Only the first three are applicable to industrialised timber framed volume production. Product and production actually strive for conformity and control, which explains why Service Life Planning could be effective and why industrialised housing is favourable regarding use of the methodology. Industrialised housing is not affected equally by the two remaining implications; specifically, they produce their products indoors with similar production methods and with a repetitive effect, which combined with owning the majority of the production process makes them gain more from Service Life Planning.

A future state could involve designing the building according to use over time, creating a new design challenge (Brand, 1994) that emphasises a performance-based approach. Service Life Planning methodology to date is a future state when it comes to the organised work at medium-sized timber framed volume producers. There are several reasons for this. Important criteria for service life information are still missing. Perhaps most products in a house fall under the low risk gradation, according to Marteinsson (2005). Useful reference service life databases are lacking as well as no mechanism or receiving part at the companies investigated.

5.3 Feedback in industrialised housing

Paper I (Meiling and Johnsson, 2007) reveals problems regarding a lack of feedback information when trying to conduct product development and apply an ISO standard for Service Life Planning. Paper II (Meiling and Johnsson, 2008a) outlines the production process at timber framed volume prefabrication as well as identifies feedback opportunities, a defect analysis is initiated in paper III (Meiling and Johnsson, 2008b), and the defect analysis is depend in paper IV (Meiling and Johnsson, 2008b). At the case study companies, keeping product development within the ongoing project is standard behaviour, resulting in old solutions regarding new problems, since full scale product development is not possible on a project basis. Product development is not a separate process and is seen as something costly that drains resources from production. The lack of central management relating to monitoring and control of house production results in difficulties regarding evaluating production and keeping track of
possible progress in product quality. The daily rate of module production is the dominating measure of process soundness.

If learning through feedback is initiated, it could be seen as a means of transforming from knowledge storage to activating knowledge capabilities, according to Mårtensson (2001). All companies perform quality audits at the factory before transport where anomalies are reported. External quality audits are also conducted on the finalised building at delivery and after a warranty period of two years (in Sweden). There is no existing link between these audits and a model for traceability of quality problems backwards in the manufacturing process is lacking. Analysis of the audits is absent. If data were to be transformed and coded at the building site when the defect occurs, the evaluation could be done more consistently, though this is yet to be tested. This means that there is no learning cycle (Deming, 1986). To continue the cycle of plan, do, check and act, the information should be distributed (plan), gathered (do), transformed (check) and applied (learn). Defects is one of the seven wastes (Likier, 2004). Together with reworking and repairing, it represents one of the best indicators of wasted effort, and waste should be eliminated by learning from experience (Wilson et al., 1993). Koskela (2004) states that the waste of making do, i.e. starting the process without all the prerequisites and settling without achieving according to standard, could be perceived as a root cause for defects. Making do is proposed to be initiated at the major stages of housing production:

1. Sales and design: design is found to start in a making-do-mode due to clients failing to gather and decide on requirements.
2. Lack of communication towards suppliers, resulting in making-do without completely designed products for commissioning.
3. Late completion of design drawings, late adjustments to customer requirements and late adjustments to procurement result in making-do with a lack of managing prefabrication.

This will inevitably be a source of continuously producing defects. The waste of unfulfilling customer requirements (Bicheno, 2004) could be considered as an internal and external customer issue. The building foundation is procured through requirements stated by the case study companies. This is successfully done towards the contractor with concise requirements for quality regarding time, size, strength and moisture. This is a matter for evaluation, which should be done for the internal interfaces in the housing production. If the internal requirements are stated, the quality will be controlled.

Problems with documentation and distribution of experience are obvious when studying the construction site. The action process to correct defects is fast and without any reflection about the characteristics of the notification in the audits. This is obviously in contrast to the proposed way of making slow decisions and working with continuous improvements (Likier, 2004, Karlsson and Åhlström, 1996). Unfortunately, feedback through quality audits among current house stock is absent within the companies, as demonstrated by the complementary study in chapter 4.1.1.

5.3.1 Construction development

Industrialised housing is a kind of project production that can be perceived as a type of manufacturing that is trying to override the peculiarities of traditional construction. Right now, it is not known where this production is leading, but new initiatives point to composite construction housing, where prefabricated elements and volumes as well as prefabricated floor structures and precast concrete foundations are utilised, Figure 25.
Figure 25. Seven storey house containing both timber- elements and volumes in Älvsbacka Strand Skellefteå 2008.

The housing industry has recently begun to transform from craft production into something as yet unidentified, but described as a mixture of on- and offsite production methods. Much of the culture and common notion is that construction is still based on craftsmanship where the construction worker is appreciated for solving every apparent situation as it evolves onsite. The ability and mandate are strong parts of the construction culture. Together without documenting the result, this is contradictory to quality thinking where the notion is for processes that are standardised and controlled to produce high quality products.

Quality in construction could be described as top down management, implemented through legislation and government demands. The product is produced towards the lowest possible demands for approved contracts. For product quality work, this attitude is insufficient. As the world waits for the next step in quality evolution, a third generation of quality management (Foster and Jonker, 2003) that goes beyond TQM, the construction industry is still considering entering the first generation, i.e. trying to implement control and reuse the information gained. The process of implementing quality in construction will take time.
6 CONCLUSIONS

This chapter summarises findings and outlines what they mean for the industrialised housing industry when it comes to quality and the lack of product development. The final section proposes further work regarding defects, feedback and continuous improvements.

Industrial housing through timber framed volume production needs to adopt a quality focus and implement experience feedback and Service Life Planning, which in turn requires well-defined products, as seen in the case study (Meiling and Johnsson, 2007).

To effectively handle demands, housing producers need to separate their product development process from their ordinary production process. If this is not done control of the process will be lost without any formal structure to implement quality management and the Service Life Planning approach, leaving it up to the company’s staff to adopt production processes rather than having a structure to support it. Since the companies have not separated from ordinary construction and established a product development department, there is no pull for experience feedback.

Industrialised housing achieves the same level of quality as traditional construction, as seen in the multiple case study (Meiling and Johnsson, 2008a, Meiling and Johnsson, 2008b). This implies that the housing firms utilise the benefits of indoor construction without adopting a manufacturing culture, and therefore miss the considered benefits of production and quality control regarding the product. It can be concluded that the reduction of defects is connected to using experience from feedback. It is identified from Lean theories and quality management theories that changes call for a strategy of continuous improvements, which in turn demands the use of feedback information. A company decision is needed to generate and handle the information through continuous improvements, Figure 26.

![Conceptual model of a quality improvement cycle at a company level.](image_url)

The possible outcome is a new level of quality, lowering the chronic level of waste instead of conducting a fire extinguishing approach, and to view the product as representing more than one project, which will affect internal and external customers willingness to consume and contribute. A zero defect strategy is not effective without analysing defects, a willingness for change and a strategy for continuous improvements. The pursuit of defects could instead be seen as a means of establishing a learning organisation and ensuring product quality in the next project.
6.1 Future work

Quality work through continuous improvements and feedback information could be an imperative strategy when choosing to utilise a prefabrication strategy within industrialised construction. Further questions and issues connected to this are, for example:

- How could defects and anomalies be effectively managed, at its source, coded and transformed, to end up where it is needed?
- What factors lead to robust experience feedback systems that are not affected by reorganisation and market changes – solutions working over time?
- How can knowledge be activated instead of filed, implying that knowledge is currently deactivated?
- How internal customer demands and requirements should be communicated to achieve enhanced quality for external customers.
- Can defect management be supported by hand held ICT tools?
- How should quality improvements be measured?
- Is the private client buying detached houses a less demanding customer? Is the quality better or worse?

When working with continuous improvements in construction a need could be foreseen to understand knowledge, learning and organisation, i.e. the culture-effects on communication between manufacturing and onsite assembly. A choice should be made regarding the desired changes and the level of action it requires – regarding organisation/goal/culture. Implementing new strategies calls for finding a sustainable measurement to compare the current state with the future state. What is not measured is not achieved.
REFERENCES


REFERENCES


References


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PAPER I

SUSTAINABILITY IN INDUSTRIALISED WOOD CONSTRUCTION

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Sustainability in Industrialised Wood Construction – A Theoretical Framework

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Abstract
Timber Volume Element prefabrication (TVE) is an industrialised production system, with low production costs, in which wall and floor elements are assembled in factories to volumes in desired dimensions before delivery to construction sites. Decisions are taken during the design process concerning the choice of material, components and installations that affect the durability of the buildings, as well as the operating and maintenance costs during their service lives, but generally with little or no consideration of life-cycle concerns. However, the Construction Products Directive (CPD) of the European Union emphasizes the importance of service life planning, and proposes that the service lives of products permanently installed in a building should be declared. Implementation of the CPD calls for development and practical use of the ISO standard 15686 (Buildings and constructed assets – service life planning).

Responses in interviews with potential TVE clients show that they have considerable uncertainties regarding the likelihood that TVE will fulfil functional requirements, and hence are concerned that the finished buildings will be less sustainable than those built using conventional materials and methods. In addition to considering the implications of this survey, two main questions are addressed in this paper: whether or not ISO 15686 can serve as a tool for strategic planning to ensure that wood-based components have satisfactory (and economically viable) service lives and whether the identification of critical cost and durability points can be used in the decision-making process when designing wood-based building products. The study focuses on stairwells in apartment blocks built by a specific TVE company. Such stairwells are key features for technical, economic and aesthetic reasons. They are public areas and exposed to intensive use. Thus, their resistance to wear, cleaning and vandalism, bearing resistance, fire safety and suitability for industrial production all have to be considered when they are designed. Empirical data collected during the development of a wooden stairwell indicate that the ISO 15686 framework is applicable to the development of wood products, but there is currently no mechanism for effectively implementing it within TVE companies.
1 Introduction

Building construction generally involves large amounts of waste, and (often) poor relationships between various parties with conflicting interests that tend to have highly adverse effects on both quality and profit (SOU, 2002). The traditional building industry is mainly project-oriented, which fosters such fragmentation and a lack of continuity (Lessing, 2006). Industrialised housing construction is regarded as a possible solution to these problems, prompting numerous efforts to develop more efficient organisational approaches. Both concrete and timber frame housing represent attempts to develop industrialised processes for constructing multi-storey buildings, which have been influenced by the procedures used in manufacturing industries, notably truck and car manufacture (Gann, 1996).

The multi-storey construction company examined in this study utilises Timber Volume Element prefabrication, TVE; a three-dimensional building system in which discrete “volume elements” containing floor, roof and wall components, together with all of the required electrical installations, flooring, cabinets, wardrobes and finishing etc. are completed in the factory, then transported to the construction site where they are assembled into complete buildings. This is preferably done according to a design-build contract, with the involvement of far fewer stakeholders than in standard, conventional contracts. Products are developed in the TVE building system during the ongoing design processes involved in each new building project (Johnsson et al., 2006), in contrast to those that generally occur in manufacturing industries, in which product development is separated from normal production (Fig. 1), providing far greater opportunities and time for testing and quality control.

![Figure 1](image-url)

Figure 1 Knowledge management (from Johnsson et al. 2006) in the building and manufacturing industries

A high degree of product knowledge is essential for optimising quality and strategic development methods. However, Johnsson et al. (2006) conclude that project-based product data management systems heavily constrain knowledge of offered products, feedback acquired through experience regarding potential problems (and/or advantages) associated with installing and using current products, and (hence) product development. In addition, TVE customers have uncertainties regarding the level of long-term sustainability of industrialised wooden constructions (Höök, 2005) and request life cycle data (Höök, 2005), increasing the need for product- and process-knowledge at all levels within the TVE company. Furthermore, as part of initiatives to improve the performance of buildings in the EU, the Construction Product Directive (CPD), drafted in 1988, has added to the imperative to implement Service Life Planning (SLP), which has been identified as a guiding concept regarding the durability of buildings (Sjöström et al., 2002) that should assist in implementing the requirements of the CPD.
Key aspects of quality include durability and reliability (Garvin, 1988), both of which are components of the “sustainability portfolio” (Trinius et al., 2005). The ISO standard 21929-1:2006 (Sustainability in building construction – sustainability indicators) aims to define a set of economic indicators related to the following phases of the life cycle of a building:

- Design
- Construction
- Use
- Maintenance
- Operation

Technical and economic demarcation of the sustainability concept also calls for well-defined products, emphasising the need to gather life cycle information and process knowledge regarding products at all stages (development, production and post-production) and at all levels, i.e. component, system and project levels, as illustrated in Fig. 2).

Since a consistent approach to product quality is currently lacking in industrialised wood construction, despite claims that it is “industrialised”, there is a need to investigate the extent to which service life planning (SLP) does (and could) support the development of timber building systems. If such an approach could be thoroughly incorporated in standard procedures the uncertainty expressed by customers regarding the long-term sustainability and durability of industrialised timber construction could be reduced. Therefore, the feasibility of incorporating sustainability considerations into the TVE building system and its interactions with associated suppliers and customers (as illustrated in Fig. 2) was addressed in the study presented here.

2 Timber volume element prefabrication

The prefabricated timber volume elements each consist of four load-bearing walls enclosing a volume. The size of the volume elements is limited to an outer width of 4.15 metres, an outer length of 13 metres and an internal height of up to 2.60 metres. The TVE company that participated in this study often runs everything in-house, seeking to implement design-build construction procedures, i.e. its staff obtain a building site, design the building according to customer demands, produce prefabricated volume elements in its factories, and then assemble and finish them on the construction site. The cost of timber materials does not contribute significantly to the potential cost savings in an industrialised construction process, instead the main driver for the cost reducing potential is the scope to increase the degree of prefabrication, improve logistics, and improve the construction process (DS, 2004).
While prefabrication has been shown to improve safety, productivity, and quality, customisation is efficiently achieved by combining standardisation and prefabrication (Gibb, 2001). However, the endeavour to reduce costs within the housing industry should not lead solely to constructing functional units at the lowest possible price, since quality must also be maintained. The key quality parameter of a building is its service life (Garvin, 1988), i.e. the length of time during which it retains its intended functionality. Functionality should be maintained throughout the building’s intended service life at predictable costs (which will depend on the building’s average annual maintenance costs and service life). Methods for standardisation and prefabrication have been thoroughly implemented in the car and truck industry, but applying similar mechanisms to buildings and constructed assets is not straightforward, due to the following five, partly interacting, reasons (SIS HB 50, 2005):

1. Complexity – a house is a more complex technical system than a car.
2. Product uniformity – normally, buildings are fabricated in small numbers, complicating attempts to impose uniformity.
3. Production uniformity – there are low degrees of automation in construction, many actors that cooperate weakly, and little quality certification.
4. Long service lives – a car has a much shorter service life than a building.
5. Environmental factors – which present substantial problems since they strongly affect the course of degradation of constructed assets, and annual mean (and extreme) values of influential environmental variables may vary dramatically in different locations, even close to each other.

Traditionally, an architect initiates product development in construction. TVE producers take more ownership of their products and consequently are also the natural owners of the product development process. Further, there is a requirement for innovative new products, rather than the adoption of existing solutions. However, inevitably no information on the long-term performance of such products is available, especially since multi-storey timber buildings have only been constructed from 1994 and hence have a short history. Thus, long-term performance parameters must be estimated.

### 3 Service Life Prediction

Efforts to formulate service life planning procedures have led to proposals that the ISO 15686 standard should be divided into eight sections, five of which (1-3 and 5-6) have been published to date. The general concept service life (ISO 15686-1, 3.1.1) is defined as the time following installation during which a building or its parts meet or exceed performance requirements (Fig. 3). For product developers the key consideration is the design life (ISO 15686-1, 3.1.4) – the intended service life of the product, with which a forecast service life (15686-1, 3.1.6) is to be compared. Ideally, this forecast will be the product’s Predicted Service Life, PSL (ISO 15686-1, 3.1.5); a forecast of its probable service life obtained in accordance with ISO 15686-2, i.e. its service life in its specific microclimate or climate conditions calculated from laboratory or real-life data. If it is not possible to obtain such a forecast an Estimated Service Life (ESL) may be obtained instead, e.g. using the factor method described in clause 9 of ISO 15686-1, for which the input is an appropriate reference service life (15686-1, 3.1.2). The factor method described in clause 9 is classified as a simple estimation method (Hovde, 2003) but its utility is unclear (Marteinsson, 2003), although it could be incorporated in the design process to assess products’ durability and as a means to develop sustainable buildings.’
More sophisticated methods are based on engineering and probabilistic approaches (Hovde, 2003). However, although the standard should be applied by those who acquire the relevant data (or specify the tests to be performed), the output should be of interest to designers who may know nothing about the detailed assessment procedures. In order to undertake a complete service life assessment, i.e. a comprehensive evaluation of the design life of a structure, the effects of time and the probability of unwanted effects must be considered, in addition to key design parameters such as resistance and bearing capacity, especially for parameters that are well defined and amenable to mathematical modelling. Work on concrete structures, for which degradation agents are well defined, indicates that the use of ISO 15686 is justified in the cases listed below (EN 206-1:2000):

- The required service life is considerably longer than fifty years.
- The required probability of failure is low.
- The environmental impact is especially aggressive or well-defined.
- The required quality of work is high.
- A maintenance strategy is required.
- A large number of similar constructions or elements will be manufactured.
- New or unconventional materials will be used.
- The sustainability of the design must be resistant to possible misconduct or mistreatment of the sub-components in the element or construction.

![Diagram of service life assessment process](image)

**Figure 3** Use of the standard from Davies (2004)

A process for forecasting service life is proposed in ISO 15686-1 (Fig. 3) and clause 6 (Fig. 4).

![Diagram of forecasting process](image)

**Figure 4** The forecasting process from ISO 15686-1.
3.1 Exploratory Case Study – Staircase Abrasion Resistance

The interactions between stakeholders were explored in a case study, following the rationale described by Yin (2003), focusing on both a staircase producer and the TVE manufacturer in their ongoing development of a prefabricated wooden staircase compatible with TVE production, through interviews and market research, and applying the ISO 15686-1 standard.

A stairwell is defined as the enclosure of a stairway, or the space around which a stair is disposed (ISO 6707-1, 4.4.15), i.e. the framed opening in the floor that incorporates the stairs. In the TVE production system the prefabricated stairwell volume element is produced in parallel with the apartment volumes. Wooden stairs have long traditions and the following qualities, which make them suitable for prefabrication (Haberman, 2003):

- Renewability
- Affordability
- Appropriate load-bearing capacities
- Workability
- Low weight.

Wooden stairs are not manufactured in-house by the TVE company, but purchased through a supplier specialising in this product. Diverse types of commercially available timber are used to build steps, but the staircases must always fulfil safety, durability and appearance requirements. Notably, the surface of the steps must be resistant to “wear” under highly abrasive conditions. Interviews with both a stair supplier, (Lindgren, 2007), and a TVE manufacturer (Risberg, 2007), have revealed the following advantages and concerns:

- Wooden stairs are more practical than other alternatives due to their workability and ease of assembly in a factory.
- There is a lack of maintenance strategy for stairwells, resulting in concerns regarding:
  - quality
  - choice of surface/cladding
  - long-term appearance of the stringer, i.e. the inclined part supporting the steps.
- Lack of aesthetically pleasing, highly abrasion-resistant, surface choices, e.g. customers often request stone cladding
- The ambition is to procure a staircase that needs no complementary work.
- Moisture damage is not acceptable in the connections between components in the stair.
- There is not, as yet, a satisfactory solution to the problem of “nosing” at the front of the steps.
- Existing staircases have not yet been optimized with respect to fire safety.
  - There is a need for more economical fire-protected staircases
- There are problems in communicating the sizes of stairwells, which sometimes result in insufficient space for prefabricated staircases.
3.1.1 Application of ISO 15686-1

In a first attempt to address these problems, the method described in ISO 15686-1, clause 6.1, was applied to the choice of flooring material on the steps, as illustrated in Fig. 4 and outlined in points a-d below:

a. In-house conditions: The stairwell is a heated vertical volume that is connected to both the outside and inside environment. There are no available data on relevant climatic variables as yet, but estimates of temperature and humidity, which should be complemented with data on seasonal and diurnal variations (Risberg, 2007), include:
   - Temperature: 17°Cmin - 20°Cmax
   - Humidity: 20% RHmin - 80% RHmax

b. The components are structured in a maintainability chart (Table 1), in which components are classified as permanent, replaceable or maintainable to various extents (numbers are estimates of service life in years).

Table 1 Maintainability chart with service life estimate (numbers indicate service life in years)

<table>
<thead>
<tr>
<th>Design life</th>
<th>Inaccessible components</th>
<th>Expensive replacements</th>
<th>Major replaceable components</th>
<th>Installations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building</td>
<td>Staircase structure</td>
<td>Stairwell flooring, wall surface, staircase abrasion surface</td>
<td>Stairwell flooring, wall surface, staircase abrasion surface</td>
<td>Shafts</td>
</tr>
<tr>
<td>50</td>
<td>50</td>
<td>40</td>
<td>25</td>
<td>40</td>
</tr>
</tbody>
</table>

c. Classification according to Vanier et al (1996). Functional element, i.e. the staircase: The case study company define their requirements for the stairs according to the numbers of apartments per floor. This is an indicator of the numbers of people using the stairs, for multi-storey buildings class A is chosen, while class C corresponds to smaller houses with a few apartments per floor. A number of possible commercially available flooring materials were identified (Table 2).

Table 2 List of flooring materials

<table>
<thead>
<tr>
<th>Flooring materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. linoleum (resilient)</td>
</tr>
<tr>
<td>2. vinyl (resilient)</td>
</tr>
<tr>
<td>3. rubber (resilient)</td>
</tr>
<tr>
<td>4. cork (resilient)</td>
</tr>
<tr>
<td>5. HPL laminate</td>
</tr>
<tr>
<td>6. stone</td>
</tr>
<tr>
<td>7. concrete, terrazzo</td>
</tr>
<tr>
<td>8. ceramic tile</td>
</tr>
<tr>
<td>9. wood and parquet</td>
</tr>
<tr>
<td>10. resin flooring</td>
</tr>
<tr>
<td>11. carpet</td>
</tr>
</tbody>
</table>

Table 3 presents a list of functional requirements for the material to be used as a top layer or covering on the steps. The actual selection procedure is not presented in this paper. The requirement list provides a basis for conceptual design (which is beyond the scope of this paper).
Table 3 Requirement list

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Abrasion resistance</td>
<td>Class AC5, IP-value ≥ 6000 according to SS EN13329</td>
</tr>
<tr>
<td>B. Moisture/water resistance</td>
<td>100 % RH, wet cleaning, ISO 62: 1998</td>
</tr>
<tr>
<td>C. Temperature resistance</td>
<td>0-180 ºC, SIS 245820</td>
</tr>
<tr>
<td>D. Impact resistance</td>
<td>Class: IC3 according to SS EN13329</td>
</tr>
<tr>
<td>E. Fire resistance</td>
<td>At least Cf -s1 according to BBR 5:512, for floor, reaction to fire, tested according to SS 024825</td>
</tr>
<tr>
<td>F. Low-slip</td>
<td>Coefficient of dynamic frictions (µ) according to SS-EN 13893, or a value &gt;35 according the pendulum test</td>
</tr>
<tr>
<td>G. Resistance to chemicals</td>
<td>Detergent, solvent, SS-En 13442</td>
</tr>
<tr>
<td>H. Replaceable</td>
<td>Maintenance, operation</td>
</tr>
<tr>
<td>I. Workability</td>
<td>With mill, cutter, saw, drill and so on.</td>
</tr>
<tr>
<td>J. Compatible with nosing</td>
<td>In the fabrication process</td>
</tr>
<tr>
<td>K. Compatible with string</td>
<td>Covering of the string</td>
</tr>
<tr>
<td>L. Able to be glued</td>
<td>On wood</td>
</tr>
<tr>
<td>M. Environmentally friendly</td>
<td>VOC test according the final draft pr EN 15052: 2006</td>
</tr>
<tr>
<td>N. Reasonably priced</td>
<td>Up to fabricant</td>
</tr>
</tbody>
</table>

d. What components need to be repairable/maintainable/replaceable? This is where a common approach is beneficial for access to life cycle data both from the TVE company (for assembled structures) and from sub-contractors that manufacture and deliver complete component structures e.g. staircases, windows, doors and installation.

The staircase manufacturer produces approximately 8000 staircases per year, mainly for single family dwellings, implying the company has strong customisation and individual design traditions and skills (a manufacturing culture). The TVE company needs approximately 100 stairs per year, but customers do not trust the existing product since it is not well suited for multi-storey high-abrasion uses. However, although it is striving to acquire manufacturing skills, it shares the project-based culture that typifies the construction sector (Fig. 5). Both companies are seeking to develop standardised products in order to gain customer confidence and trust, but it will not be possible to transfer management tools from the industrial sector to the construction sector without substantial reorganisation and a culture-shift (Riley, 2001). The findings of the survey indicate that the house producer desires to purchase standardised staircases, while the staircase manufacturer handles their production as custom-made, hence there is an information gap, resulting in low fulfilment of functional requirements and high expenditure. Thus action needs to be taken to introduce a systematic approach to develop a more effective product development interface, and thus closer to optimal products.

Figure 5  Product development as a catalyst for structuring processes.

Neither the staircase manufacturer nor the house producer apply an overarching systematic product development approach, e.g. Quality Function Deployment, QFD (Dale, 1999), or other systematic methods for problem-solving, but the demand for new products, both from manufacturers and customers, indicate that there is a need for such an approach.
4 Conclusions

Knowledge of both the performance requirements and likely performance over time of products under development is essential for reliable forecasts of their service lives. The exploratory case study presented here shows that efforts are being made to develop new TVE products, but lack of appropriate management structures is hindering the quality assurance of the product development. The study also reveals that there is a lack of available data for executing SLP through the ISO standard. However, the obstacles to applying knowledge from the car industry are less formidable in TVE companies than in ordinary construction companies. Of the five hindrances listed in the ISO user guide (Complexity, Knowledge of service life, Environmental considerations, and Uniformity regarding the Product and Production) only the first three are applicable to TVE production. Although standardising house production is more complex than standardising car production (Gibb, 2001), TVE construction is more suitable for industrial production than conventional house construction, and thus further research on the scope for applying the ISO 15686 standard to it is warranted.

Since TVE producers strive to control their products their demands on their suppliers are greater than those of conventional construction companies. TVE producers are developing from conventional building firms with in-house production methods into industries in which quality control is a major concern. This trend is also increasing the scope for incorporating Service Life Planning (SLP), which requires well-defined products, as seen in the case study. There is of course a strong motive for implementing SLP when customers declare a lack of trust in the offered products. This in turn forces the product owners, manufacturers, designers and other relevant stakeholders to deal with this issue. In order to be able to effectively handle SLP demands, the TVE producers need to separate their product development process from their ordinary production process, Fig. 6. If this is not done control of the process will be lost and there will be no formal structure for implementing the SLP approach, leaving it up to the company’s staff to adopt it, rather than having a structure to support it.

For the building industry at large, there are two strong incentives to use SLP. First, the building codes in Sweden are formulated with performance-based functional requirements, providing a framework for applying SLP methods, which are also performance-based (Trinius et al., 2005). Second, the conservative building industry finally has a tool that can reduce the uncertainties concerning new products it develops.

Incorporating SLP planning in the TVE producers’ product development process would provide opportunities to:

- Optimise construction according to customer demands – by improving knowledge of maintenance needs and when components will probably have to be replaced.
- Specify specific features and advantages within the building system – by comparing different solutions and components.(cont.)
- Communicate and verify functional demands – by matching building performance level to functional and budgetary requirements.
4.1 Future work

No data are available as yet to facilitate the development of fire-safe staircases in multi-storey houses. The ISO 15686 standard does not yet provide reliable procedures for calculating absolute forecasts of relevant parameters (Davies, 2004), but it may at least provide a suitable framework for comparing alternatives, as suggested in the ISO standard guide. For further work a wooden stairwell with new innovative abrasion layers could therefore be compared to a concrete structure, since this kind of structure has the trust of customers and has proven to provide reliable service lives.

The gap between stakeholders, with different company cultures (Riley, 2001), calls for a wider survey regarding the needs (inter alia) of architects, facility managers and customers. Applying findings from this survey to product development requires the adaptation (and implementation) of appropriate quality management procedures, based on sound data, during production decision-making (Dale, 1999).

Since stairwells with wooden staircases in multi-storey buildings are a new phenomenon in Sweden, knowledge of relevant decision-making points in product development is not available. Therefore a product survey of existing stairwells, focused on wear and technical degradation, should be conducted. Since degradation could be linked to functional requirements such a survey could provide essential information for the development of new, improved staircases, and be highly valuable for systematic product development tools, e.g. QFD, as well as for implementing Service Life Planning.

References


EXPERIENCE FEEDBACK AT INDUSTRIALISED HOUSE BUILDERS

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EXPERIENCE FEEDBACK AT INDUSTRIALISED HOUSE BUILDERS

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ABSTRACT
In lean theories as in quality management, the notion of continuous improvement is strong. Experience from an earlier production cycle should be fed into the next cycle. The framework of lean production offers a structure for experience feedback to take place. The industrialised house builders would benefit more from experience feedback than traditional construction firms would, since the degree of repetitiveness of their work is higher. The degree of prefabrication in industrialised housing ranges from manufacturing open walls and floors up to producing entire volume modules with complete interior cladding. The higher the degree of prefabrication, the stronger is the clash between construction and manufacturing, since the traditional construction process does not cater for the need for early design decisions that are rigid throughout the building process. This paper aims at exploring the production process at three industrialised housing companies seeking feedback opportunities and implications. An explorative research method is used where interviews with the participating companies show that initiatives and opportunities exist, but not in a consistent way. The transformation of information and knowledge into useful design input could be seen as a bottleneck in production process.

KEY WORDS
Experience feedback, industrialised housing, multi storey building, timber volume element prefabrication.

INTRODUCTION
The construction industry is based on craftsmanship and the construction hero is someone who quietly handles every appearing situation with a sufficiently good result. If quality work in manufacturing relies on, e.g., repetition, standardisation, and follow-up, then construction is about uniqueness, responsiveness to problems, and flexibility in solutions. Therefore, the clash between the construction culture and the thought of quality management is large.

There is a category of construction companies that have met the contradiction between construction and manufacturing; the industrialised house builders, in this paper defined as those who produce houses in a closed factory environment with one evident process owner and a clear product goal of repetition in housing design and production where there is mostly assembly at the building site. Lessing et al. (2005)

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suggested eight characteristic areas that constitute the concept of industrialised housing namely: (1) planning and control of the processes, (2) developed technical systems, (3) off site manufacturing of building parts, (4) long term relations between participants, (5) supply chain management integrated in the construction process, (6) customer focus, (7) use of information and communication technology (ICT) systematic performance measuring, and (8) re-use of experience. In this paper the term traditional construction is understood as a construction project with low fulfilment of these eight characteristics. Industrialised housing companies have made an effort to distance themselves from the three interrelated peculiarities that distinguish construction from manufacturing, namely (1) site construction, (2) one-of-a-kind production, and (3) temporary organization (Vrijhoef and Koskela 2005). Industrialised house builders can be inspired by lean production theories within the company itself, but the construction site still functions according to traditional construction logic.

An extensive governmental evaluation (SOU 2000:115) of the Swedish construction industry states that knowledge in construction is fragmented, resulting in an inability to transfer knowledge from one project to another, and a similar investigation was conducted in England (Egan 1998). Yet another Swedish government report (Sigfrid 2007) calculates mistakes to have an extensive impact on the production price, the cost for correcting defects after moving in could be up to as much as 95 million euros. Defect examination in construction is not uncommon, e.g. Josephson and Hammarlund (1999) and Ilozor et al. (2004). Industrialised house builders in Sweden have chosen to address problems, regarding knowledge transfer and defects, through prefabrication in a controlled factory environment. One challenge, and opportunity, to becoming more industrialised is to change the company culture towards a process oriented production and work with feedback and reuse of experience (Lessing 2006).

This paper presents a case study of the construction process at three industrialised house builders, with a focus on practical feedback initiatives. The three companies use a timber volume element prefabrication method and cater to the Swedish market. This study does not comprise industrialised single family housing i.e. manufactured housing. The hypothesis to view houses as products instead of projects is based on the understanding and view of how industrialised housing can benefit from lean and quality management theories.

THEORY

LEAN PRODUCTION

The basic idea of lean production is to reduce unnecessary operations, waste, with simple methods to promote increased flow targeted at creating customer value (Womack and Jones, 2003). Instead of producing to stock, the concept of pulling, i.e., manufacturing when the need arises, creates a flow through the production system. Value is created by the flow, both for internal and external customers. Value streams through the process, both within the process itself but also from supply chains. Perfection is the basic lean thinking principle meaning continually striving towards producing precisely what the customer wants and delivering the product when expected while eliminating waste (ibid.). Perfection is a way not the means, through
identification of a future improved state that will always be advanced when reached (Rother and Shook 2003).

In 1992, one of the first parallels were drawn between manufacturing industry and construction when (Koskela 1992) defined the principles that laid the foundation to what is known as lean construction. In lack of an industrial manufacturing process Koskela (1992) issued the TFV framework, referring to transformation, flow, and value, with a base in production and operations management. The introduction of transformation as an element in lean theory reflects the construction industry’s idea of an object being gradually enhanced by craftsmen not necessarily organised in a flowing manner. Production has to be performed using transformation of inputs into outputs where materials, and information, flow through value and non-value adding activities with value for the customer as the end goal.

Björnfot (2006) argues, from an industrialised construction perspective, that lean production management is restrained by the project-oriented construction process, and thus obstructing perfection. Bertelsen and Sacks (2007) is making a historical survey, arguing for a new understanding of construction and proposes construction projects to be linked in a complex network, constituting a web of flow. The development of industrialised construction is an ongoing process, in close relation to the development of Lean Construction. Höök (2008) states that industrialised culture changes focus from organizational- and project learning, towards building in knowledge into the process instead of in the people, and hence facilitate knowledge feedback in a consistent way. The importance of a cultural change and a top-down strategy combined with bottom-up tools of lean manufacturing is also supported by Liker and Lamb (2002). A key element in the pursuit of perfection is learning and feedback (Liker 2004).

ENGINEERING KNOWLEDGE AND KNOWLEDGE BASED ENGINEERING

There are several initiatives in the area of knowledge management (KM) through information technologies, e.g., KM systems using blogs and wikis for capturing best practice and enabling information pull (Ahn et al. 2007, Egbu and Botterill 2002, Shelbourn et al. 2006). This is understood as answering the question: What is the design rationale and what are the requirements for how the building system and its basic technical solutions should be chosen in order to meet performance requirements? Improved design decisions are bound to product knowledge, thus the capture of information for later use in the design process is vital for fulfilling requirements. Knowledge based engineering (KBE) is a manufacturing industry life cycle approach to knowledge management (Egbu and Botterill 2002, Stokes and MOKA Consortium 2001). The KBE methods/approach is initiated in order to enhance the effectiveness and efficiency of engineering design, normally by creating design support tools in a CAD environment. The product knowledge, i.e., configuration and engineering knowledge, is formalised into design rules available in the CAD environment. The KBE design process is denoted a product model and the actual information is referred to as a knowledge base (LaCourse 1995). Information such as geometry, material type and performance as well as process information can be stored. The KBE knowledge base, is what could be defined as an active design procedure manual, with the ability to improve through feedback from production, tests, and quality audits (LaCourse 1995). The KBE product model, unlike an
engineering team, never forgets; it computes numerous design models in a short time and thus reaches build able designs with fewer resources. In construction, a theoretical framework for learning through project feedback was presented by Kärnä and Junnonen (2005). They state that learning takes place on four different levels, (1) organisational, (2) individual, (3) construction and (4) relationship learning, and they conclude that learning is a key ingredient with successful companies in terms of value creation.

ISO STANDARDS AND QUALITY WORK

The Quality management system is the part of an organisations management system that is focused on achievement of results, in relation to quality objectives, to satisfy needs, expectations and requirements of interested parties, as appropriate (ISO 9000:2000). It is defined as (ISO 9000:2000 3.2.3) “the management system to direct and control an organisation with regard to quality.” Product quality is defined as (ISO 9000:2000 3.1.1) “degree to which a set of inherent characteristics fulfils requirements.” Thus the characteristics and the requirements chosen are what makes the product and the management system is only a framework. The most widely used standard for implementing such a quality management system is the ISO 9000 series. This set of standards is implemented mostly because of customer requirements and the ISO certificate is the most desired outcome (Poksinska 2006). It is clear that the outcome of the implementation reflects the reason for applying and the most decisive means for successful outcome, when implementing ISO 9000, is a will to manage the company regarding quality (Gustafsson et al. 2001). Lean theory offers a management foundation for implementing continuous improvement initiatives expanding the governing construction logic domain, without life cycle considerations, into a Lean service life domain. A key difference between manufactured products and housing is the view of product quality being decisive of service life and of maintenance costs required to attain intended service life. The general concept service life (ISO 15686-1, 3.1.1) is defined as “the time after installation during which a building or its parts meets or exceeds the performance requirements.” Service life planning through the ISO standard portfolio (ISO 15686) is suggested to contribute to enhanced building quality, strengthened collaboration between actors, and minimised life cycle costs (SIS HB 2005). Emphasis on Service Life Planning (SLP) as an effort to ensure building performance was initiated when the Construction Product Directive (CPD) was issued in 1988 (The Construction Products Directive 1988). Sjöström et al. (2002) states that SLP was identified as a guiding concept regarding durability of buildings, that should be of help in implementing CPD. Estimating service life should be done through feedback of actual performance measurement. Service life planning could be considered a complementary framework for life cycle approach, also supported by KBE, offering a quality approach to product enhancement in construction.

METHOD

The multiple case study involves three companies utilizing industrialised prefabrication production. The companies are medium-sized, counting approximately 100-150 employees, with around 20% of their staff working in design and administration, and the remaining staff engaged in production. All three companies
use timber for the load-bearing structure and have chosen to manufacture modular houses (volume elements) inside a factory, reducing the building site to final assembly. With the modular technique buildings can be up to five stories high. The prefabricated timber volumes consist of four load-bearing walls enclosing the volume. The size of the volume elements is limited to an outer width of 4.15 meters, an outer length of 13.00 meters and an internal height of the volume element up to 2.60 meters. Empirical findings are based on data gathered through interviews, observations and archival studies in order to understand the industrialised production process. Interviews were conducted with key persons representing management (3 companies), factory production (3 companies) and assembly (site managers of 5 assembly teams). Five different field trips to building sites were conducted. Semi-structured, in-depth interviews were performed with the head of quality work at one company, two site managers at one company, the head of sales at two companies and two production managers at one company.

**CASE STUDY**

The organisation of production in the studied companies is quite clear, however not process-oriented in any formal way. Building projects follow predefined paths, which involve multiple activities, see figure 1. The figure also illustrates how manufacturing- and construction logic meets in the industrialised building process. The process of producing a house has a long start-up phase, where communication with the client and authorities dominate the activities to eventually reach a product definition for the building. The company often runs everything in-house, using a design-build contract, i.e., they design the building according to customer demands, they produce prefabricated volumes in their factories, and they assemble and finish them on the construction site. Design, manufacturing, and erection, takes respectively 12+4+4 or a total of 20 weeks. Most activities remain in-house, while some are performed by external consultants. Building- and guarantee inspections, see figure 1, are both compulsory through contract, in Sweden regulated and formalised, through a non-profit-making association of influential actors in the construction industry, and presented in two regulations; one is general regulations for construction, AB04, and the other is specialised for design build contracts, ABT94. Regulations stipulate the guarantee limit to two years for material and inventory.

![Figure 1: Time frame for the typical building project with a simplified model of activities during design, manufacturing and commissioning.](image-url)
BRIEFING

Briefing consists of 4 weeks to allow for early client contacts, 12 weeks receiving a building permit, 8 weeks for design for tender, and 12 weeks tender negotiations and acceptance. During this period both economical and technical design issues are addressed as well as architectural aspects. The sales department consists of 2 to 3 individuals of which one person is assigned to support long-term customers. Architectural work is done both in-house and with customer-selected external architects, both of which are skilled in the volume element prefabrication system. After sales, a start meeting is initiated where sales, design, purchase, production and assembly are represented. This is where the object specific demands are investigated; this is also when the project leader is appointed.

All of the investigated companies try to promote early customer choice of standardised design solutions. Two companies have assigned the work of documenting such a company standard, i.e., technical platform. Early design work is organised under the sales department, and is supposed to be supported by a skilled senior design employee, but due to capacity problems this designer is occupied with design- and production.

THE DESIGN PROCESS

The same kind of standardisation appears for these companies in the design process, by defining standard joints, standard stairwells, standard wall and floor sections, etc. Since the layout of the building affects the manufacturing to a large extent, strategic alliances with architects and customers are sought to streamline the design process. Drafting of the building envelope is handled by the companies themselves, while HVAC drafting, structural design, electrical drafting and life-cycle costing are handled by external consultants to a varying extent.

Common for the companies is that building design and HVAC installation is performed in two stages: first, the building envelope is divided into modules suitable for manufacturing; second, the detailed design where the elements building up each module are drafted on manufacturing drawings. Standard CAD software for construction is used to produce drawings printed on paper. A bill of materials in Excel is produced as by performing a quantity take-off directly from drawings. Ordering of materials is done manually, based on the bill of materials. Communication is done mainly via e-mail or phone. There is no visualisation of design activity progress. Quality control of drawings are scheduled but not executed in order to save time and not causing any manufacturing delay.

THE MANUFACTURING PROCESS

Data from design is transferred in printed format, and sometimes even re-organised or re-drafted before being directly applicable in manufacturing. None of the studied companies have automised their production plants, but plans exist to do so. The factory seems to work as a stand-alone production unit and the drawings produced have a strong resemblance to those used for on-site construction. The capacity of the production plants vary, on average 150 m2 of finished modules are produced daily.

Rules and limitations regarding volume assembly exist at different levels in the organisation, but they are not documented consistently. Many of these rules have not
been documented at all and exist only in the minds of the employees. The rules are therefore not transparent in design, creating unnecessary rework between design and manufacturing. Once the wall elements are manufactured and assembled to volumes, internal cladding, painting, and decoration starts. The workers use printed drawings to keep track of work tasks for each module.

Before storing finished volumes, an inspection is done and deviations are reported. All missing equipment or undone work is listed; documentation is done in different software, including Excel, Outlook, and company-developed software. This documentation is not used for any other purpose than as a check list for ordering material or assigning labour to correcting defects, there is no practice of follow-up after closing the issue. Data and experience from projects are kept in archives related to a specific project, but they are not related to the production process. There is no clear process orientation or process leader, which can disturb co-operation between departments. The ownership of improvements in activities or product development does not have an appointed function. No person is working fulltime on quality issues or product development.

ASSEMBLY ON SITE

The modules are delivered to the building site by truck and their delivery time is set scheduled to minimise site work. The work on site is carried out by small, tight, groups of both in-house teams and external carpenter firms. These teams are moving from building site to building site, and have inherent knowledge about the practical aspects of the building platform. At the building site, information flow is a problem. This is addressed by meetings and short education sessions but these do not take place on a regular basis. A common problem is the lack of detailed standards for specific work task; all teams have their own solutions, when it comes to e.g., edging, carpet joints, and doors. All companies rely on a few long term relations with skilled workers. One company has a newly formulated imperative: when a new group is accepted for assembly work at least one skilled worker, appointed by the company, is required to participate in the erection of the first three buildings.

FEEDBACK INITIATIVES

Data is organised with building projects as the base, which is natural while the project is current, but difficult when the project has become an experience. Product development is not a separate process within the companies, but rather an activity that arises in project after project. Information is dependent on individuals, there is no central management system that controls the progress of the house production process; therefore it is difficult for individuals to keep track of the progress. All of the investigated companies have initiated meetings, with staff from design, prefabrication and assembly, at least once, where discussions have been documented in the intention of further feedback analysis. One company has appointed groups, representing assembly, for contributing feedback and reporting on new solutions. But no body is dealing with the incoming information, from these initiatives, and transforming it to engineering knowledge and changing the platform – the building system. One company working with long term commissioned assembly crews have had some projects with zero defects at delivery; this is somewhat of a record in the construction industry, but there is no investigation connected to this achievement. External quality
audits are made on the finalised building at delivery and after a guarantee period of two years (in Sweden). There is no existing link between these audits and no model is established for traceability of quality problems backwards in the manufacturing process. The analysis of the audits is absent. The action process for correcting defects is fast and non-reflective about the characteristics of the notification in the audits. Feedback through quality audits among current house stock is unfortunately absent.

DISCUSSION

The prefabrication of timber frame volumes, as one form of industrialised housing, has improved since well over 50 years in Sweden. Timber volume element prefabrication, as a concept for multi-storey construction is a novel production form in Sweden since 1994. Recent prefabrication initiatives gaining much attention on the Swedish market, for its high degree of completion are the two systems NCC Komplett (concrete elements) and Open House (steel frame volumes). Recently they shut down their factories, NCC (2007) and Open House (2008). Both argue they advanced too fast with too many technical solutions. The timber volume producing companies represents a stable and competitive actor on the market when it comes to simple, repetitive houses as sheds, student homes, etc. These companies are rather small and do not invest in radical changes. The industrialised house builders would benefit more from experience feedback than traditional construction firms would, since the degree of repetition of this work is higher also in the sense that the process owner takes responsibility for the entire product. Thus of the five hindrances for comparing houses and cars, listed in the ISO user guide for service life planning (SIS HB 50, 2005), (1) Complexity, (2) Service life, (3) Environment, (4) Product uniformity and (5) Production uniformity, only the first three are applicable as products and production is uniform in industrialised housing production. Even if houses are not cars, a comparison Gibb (2001) and others have argued should be treated with caution, the industrialised companies are closer to industrialised production and thus have possible a greater opportunity to take responsibility of long term quality and feedback. All three companies in the case study are working with design-build contracts, and long term relations with suppliers. Individuals and construction teams are organised according to industrialised construction conditions where relations remain the same from project to project. This implies that in the perspective of learning, these companies will gain advantage of organisational and construction team learning (Kärnä and Junnonen 2005) due to less implications from individual and relationship learning.

If a service life approach was applied during briefing and design this could facilitate the utilisation of existing quality audits and inspections, creating value from defect notations in the inspection documents. As the designers are pressed for time they instead choose to rely on personal experience rather than facts originating from detailed examination of the inspection protocols. The transformation of information, into product knowledge and then reuse, could indeed be considered as a bottleneck in production. In timber element prefabrication companies, KBE could serve as a model in order to formalise solutions and to ensure the capture of building system knowledge in a systematic and sustainable way by starting to find ICT solutions. KBE is not utilised within timber volume element prefabrication. This is in part due to the small series of houses and partly due to the product and its interfaces not being
defined. Furthermore a product development process appears to be non existent with the observed timber volume element prefabrication companies. A clear receiver for KBE efforts is therefore lacking. The importance and difficulty of capturing, structure, and transforming information within the company for sustainable use in a continuous process is not given enough resources. A product development approach to construction recognises the importance of feedback to satisfy the customer (Ulrich and Eppinger 2004). This is adopted by the European community through the CPD directives and the service life planning standards (Trinius and Sjöström 2005).

Ironically, one obstruction towards lifecycle approach seems to be working with ISO quality management systems. The system is being mistaken for implementing a feedback system. A quality management system, according to ISO 9001, only offers a framework for enhancing the level of quality on both processes and products and it should not be implemented in fear of losing business or considered a maximum achievement vs. quality management (Dale 1999). This is a common case in the SME business (Gustafsson et al. 2001). The basic thought is to actively prevent, change, and improve rather than control and repair (Bergman et al. 2003). Routines within a quality system, as practised in construction, is not used for feedback unless defects or mistakes have an economical implication with other stakeholders (Persson 2006).

CONCLUSIONS

Industrialised housing companies have the opportunity to apply a life cycle approach to their products because:

- They own a significant part of the construction process, i.e., the processes of briefing, design, fabrication, and construction.
- They are striving to achieve a product standard and thus gaining a repetitive effect.
- They utilise indoor production in a controlled environment.

The transformation of information and knowledge is a bottleneck in production because:

- Data and experience from projects are kept in archives related to a specific project; experience should rather be stored in a database, where improvement suggestions from each project are linked to a production process.
- Industrialised housing companies utilise experience on an individual basis without allocated resources.

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REFERENCES


PAPER III

FEEDBACK IN INDUSTRIALISED HOUSING — WHY DOES IT NOT HAPPEN?

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FEEDBACK IN INDUSTRIALISED HOUSING – WHY DOES IT NOT HAPPEN?

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The construction industry is based on craftsmanship and the construction hero is someone who handles every appearing situation with a somewhat good result. Quality work in manufacturing relies on repetitiveness, standardisation and follow-up, whereas construction is about uniqueness, responsiveness to problems and flexibility in solutions. A category of construction companies have met the contradiction between construction and manufacturing – industrialised house builders. This category of companies work with the prefabrication of building parts for later assembly at the building site. The degree of prefabrication ranges from manufacturing open walls and floors up to producing entire volume modules with complete interior cladding. In lean theories as well as quality management, the notion of continuous improvement and experience feedback is strong. Yet, why is this mechanism almost non-existent with traditional construction companies? Industrial house builders benefit more from experience feedback than traditional construction firms, since the repetitiveness is higher. This paper aims to explore why experience feedback, in Sweden, does not function in today’s industrialised building process. The manufacturing process of four industrial house builders in Sweden was studied and mapped. The results show that much focus was put on streamlining the production process at the factory, but that experience feedback between departments at the company was small and non-existent from quality audits within the company. A change in company culture and leadership is needed to start addressing this problem.

Keywords: Industrialised housing, Quality management, Feedback

INTRODUCTION

Industrialised housing in Sweden is identified to have the potential to increase efficiency and control, lower costs and increase quality (SOU 2002, 2000). The emerging industrialisation in construction is following an international trend (Apleberger, Jonsson and Åhman 2007) e.g. the Egan Report (1998) argues that construction must turn into a manufacturing process in order to become more efficient. The development of timber frame prefabrication on the multi-storey market was enabled through the introduction of functional building codes in 1994. The high strength/weight ratio for wood implies the possibility to handle prefabricated units over large transportation distances (Höök 2006). The degree of prefabrication ranges from manufacturing open walls and floors up to producing entire volume modules with complete interior finishing. The method of using volume-based timber construction moves 90% of the work to factories (Ibid.). Höök (2006) states that industrialised housing, when aiming for standardized and predictable processes,
changes the company culture from organizational learning and learning between projects, and will develop towards building in knowledge into the process instead of in the people, thus facilitating knowledge feedback in a consistent way. Liker and Lamb (2002) also support the importance of a cultural change and a top-down strategy combined with bottom-up tools for lean manufacturing. Sigfrid (2007) calculates mistakes in construction to greatly impact the production price, i.e. the cost for correcting defects after moving in could be up to €95 M. Josephson and Hammarlund (1999) calculate the cost for defects during a project to 6% of the production cost. In an average building project the cost of poor quality is 15% (Josephson and Saukkoriipi 2005). Hence, feedback and re-use of experience is an urgent field that causes both monetary and product quality implications. Industrialised house builders could benefit more from experience feedback than traditional construction companies, due to the higher repetitiveness and one process owner taking responsibility for the product.

This paper presents a case study of the construction process at four industrialised house builders using timber volume element prefabrication on the Swedish market. The analysis is made with a focus on scrutinizing feedback possibilities. The research question is the following: If industrialised house builders have control over large portions of the process, why does experience feedback not function?

INDUSTRIALISED HOUSING

A prefabrication strategy changes construction companies from object-oriented builders focusing on on-site construction to process-oriented manufacturers taking larger control of the value chain with the reduction of workflow variability due to repetition in operations (Höök 2006). Theoretically, such companies have all the prerequisites to control the processes and the resources used, moving value-added activities up the supply chain and into a controlled environment (Nasereddin, Mullens and Cope 2007). Lessing et al. (2005) suggested eight characteristic areas that constitute the concept of industrialised housing: (1) planning and control of the processes, (2) developed technical systems, (3) offsite manufacturing of building parts, (4) long-term relations between contractors, (5) supply chain management integrated in the construction process, (6) customer focus, (7) use of information and communication technology (ICT), (8) systematic performance measuring and re-use of experience. Diekman (2003) presents a set of characteristic lean principles: standardisation, culture/people, continuous improvements/built-in quality, eliminate waste and customer focus.

A timber volume element is a closed three-dimensional structure built up by timber framed elements completed in a factory. The timber volume element contains four load-bearing walls (exterior walls or volume separating walls), a system of joists, interior roof and partition walls, each representing an element. The size of a volume element is limited to an outer width of 4.15 meters and an outer length of 13 meters. The production is managed in eight main stages - element production (walls, floors, etc.), assembly to volume modules, interior cladding and installations, exterior completion and covering, storage of volumes, transportation to building site, erection of modules on site, and finalised building.

QUALITY MANAGEMENT

Total Quality Management (TQM) is defined as both a philosophy and a set of guiding principles (Dale 1999, Bergman and Klefsjö 2003). Quality work at a
Industrialised housing and feedback

company is often connected to a routine exercise without any thoughts of implementing a system for enhanced product quality, such as with ISO 9000 standards (Nee 1996). The result is then to manage documentation aspects of getting or maintaining the ISO certificate rather than reaching desired quality goals (Gustafsson et al. 2001, Lam and Ng 2005).

The values of TQM is summarized in five cornerstones; (1) focus on the customer, (2) base decisions on facts, (3) focus on processes, (4) improve continuously, and (5) let everybody be committed (Dale 1999). The cornerstones are supported by a set of tools, values and methodologies (Bergman and Klefsjö 2003), many of which are also used within the Lean production system (further discussed in the following chapter) (Arnheiter and Maleyeff 2005). The formalisation of continuous improvements is often demonstrated by the PDCA (Plan, Do, Check, Act) learning cycle and by improvement tools and methods, such as root cause analysis (RCA), (Wilson, Dell and Andersson 1993, Jones et al. 1999, Arnheiter and Maleyeff 2005), and techniques like cause-and effect- and tree diagrams. Low and Peh (1996) suggest a framework for implementing a TQM quality system in construction, though the impediments are also summarised by Low and Teo (2004), who state that the success of TQM is yet to be proven in construction. When learning about improvement systems it is difficult not to mention yet another quality management system originating from TQM and Motorola Corporation in 1985, i.e. Six Sigma. A customer focus is again emphasised, recognising that quality is the responsibility of all employees and that employees must be trained to achieve (Pyzdek 2001). In Six Sigma, initiatives similar to learning cycles in TQM are used to improve the existing business process and new product or process designs for predictable, defect-free performance. Six Sigma is associated with defects and quality, and Lean production is linked to speed, efficiency, and waste (Hahn, Doganaksoy and Hoerl 2000). Both are production oriented, but because Six Sigma is a disciplined and a highly quantitative approach (Hahn, Doganaksoy and Hoerl 2000), it could be argued premature to use in construction with undefined and shifting processes. However, Abdelhamid (2003) and Arnheiter and Maleyeff (2005) argue for Six Sigma to be transforming from a highly developed technical, statistical system that only focuses on minimising variations and defects to a management program in pursuit of customer satisfaction.

LEAN THINKING

Lean Production

The basic idea in lean production is to reduce unnecessary operations and waste with simple methods to promote increased flow targeted at creating customer value (Womack and Jones, 2003). Instead of producing to stock, the concept of pulling or manufacturing when demanded creates a flow through the production system. Value is created by the flow for both internal and external customers. Value streams within the process itself and from supply chains. Perfection is the basic lean thinking principle, meaning to continually strive towards producing precisely what the customer wants and deliver the product when expected while eliminating waste (ibid.). Perfection is a way not the means through identification of a future improved state that will always be renewed when reached (Rother and Shook 2003). The elimination of waste is pursued through continuous improvement of the production system by using the same tools and methods as in TQM, such as root cause analysis and the technique of asking five whys (Jones et al. 1999). To achieve this, Toyota has implemented so-called quality circles (Shingo 1986) consisting of cross functional groups of operators from
different functions. Everyone is involved and responsible to come up with suggestions for improvements. In addition, everyone is empowered to stop the production line if mistakes are detected.

**Lean Construction**

In 1992, one of the first parallels was drawn between the manufacturing industry and construction when Koskela et al. (1992) defined the principles that laid the foundation for what is known as lean construction. In lack of a flowing manufacturing line, Koskela (1992) issued the TFV - framework: transformation, flow and value, with a base in production and operations management. The introduction of transformation as an element in lean theory reflects the construction industry’s idea of an object being gradually enhanced by craftsmen, though not necessarily organised in a flowing manner. Production has to be performed using transformation of inputs to outputs, where materials and information flow through value and non-value adding activities with customer value as the end goal. Being a project-oriented framework, lean construction so far lacks the long-term strive to perfection. To improve performance a new understanding of construction and its product is proposed (Bertelsen and Sacks 2007), though for now project organisation is not the best way to deliver value (Winch 2006), particularly when facing the difficulty of having temporary organisations cling to value generation. Kärnä and Junnonen (2005) present a theoretical framework for learning through project feedback. They state that learning can be divided in four dimensions i.e. (1) organisational, (2) individual, (3) construction and (4) relationship learning, and conclude that learning is a key ingredient within successful companies in terms of value creation. The difficulty with learning in construction projects is documented by e.g. Anheim (2001), Persson (2006), Shelbourn et al. (2006) and Ahn et al. (2007). Vrijhoel (2005) blames the three peculiarities of production in construction, i.e. site construction, one-of-a-kind production and temporary organization, as obstacles. A joint venture of Six Sigma and Lean in construction projects has recently been proposed (Abdelhamid 2003, Arnheiter and Maleyeff 2005).

**METHOD**

The manufacturing process at four Swedish house manufacturers is described and probed to document the feedback management regarding the technical solutions utilised as well as the overall quality in the product. The companies are small and medium sized (see Table 1).

<table>
<thead>
<tr>
<th>Case Company</th>
<th>No of employees</th>
<th>Main products</th>
<th>Turnover (MEuro)</th>
<th>No. of storeys</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>220</td>
<td>Schools- and office buildings</td>
<td>38</td>
<td>Mainly 1-2</td>
</tr>
<tr>
<td>B</td>
<td>135</td>
<td>Multi family- and student dwellings</td>
<td>42</td>
<td>Mainly 4-5</td>
</tr>
<tr>
<td>C</td>
<td>300</td>
<td>Multi family- and office buildings</td>
<td>42</td>
<td>Mainly 1-4</td>
</tr>
<tr>
<td>D</td>
<td>35</td>
<td>Schools- and office buildings</td>
<td>7</td>
<td>Mainly 1-2</td>
</tr>
</tbody>
</table>

Empirical results are based on data gathered through interviews and observations from October 2007 to February 2008, along with archival studies to understand the
Industrialised housing and feedback

industrialised production process. Interviews were conducted with individuals representing management (four companies), factory production (four companies) and assembly (site managers of five assembly teams). Five different field trips to building sites were conducted. Semi-structured, in-depth interviews were performed with the quality manager at one company, two site managers at one company, the sales manager at two companies and two production managers at one company. Building inspections from 16 building projects were examined representing 958 prefabricated volume modules. A total of 2,829 defects were sorted by their origin (see Figure 1). To evaluate the possibility of using existing inspections, a population representing 20% of the total production was explored. Also, guarantee inspections from 9 projects were examined, representing 909 modules and 490 defects.

![Figure 1 Construction process timeline with experience feedback from audits, case study is performed from building- and guarantee inspections.](image)

Building and guarantee inspections, compulsory through contract in Sweden, are regulated and formalised through a non-profit association of influential actors in the construction industry. A rigorous set of rules is presented in two regulations, i.e. general regulations for construction, AB04 (AB 2004), and design build contracts, ABT94 (ABT 1994).

**TIMBER VOLUME ELEMENT PREFABRICATION CASE**

The organisation in the studied companies is not process-oriented in any formal way. Building projects follow predefined paths involving multiple activities (see Figure 2). The companies often run everything in-house, seeking a design-build contract. During design, manufacturing and erection, the building is thoroughly defined, manufactured and erected. Most activities remain in-house, while some are performed by external consultants.

![Figure 2 Time frame for the typical building project with activities during design, manufacturing and commissioning.](image)
Briefing

Briefing includes 4 weeks of early client contacts, 12 weeks for the building permit and 8 weeks to design tender and 12 weeks for tender negotiations and acceptance. Financial and technical design issues as well as architectural aspects are addressed during this period. The sales department consists of one person in company D and two to three persons in companies A, B and C. The architectural work is conducted in-house and with external architects, both of which are experienced in the volume element prefabrication system. After sales, a start meeting is initiated where object specific demands are investigated; this is also when the project leader is appointed. Two companies are assigned the work of documenting a company standard, i.e. technical platform, as part time work. Early design work is organised under the sales department and is supposed to be done by a skilled senior design employee, but due to capacity problems this person is often occupied elsewhere.

The Design Process

Standardisation appears for these companies in the design process, by defining standard joints, standard stairwells, standard wall and floor sections, etc. Since the layout of the building greatly affects the manufacturing, strategic alliances with architects and customers are sought to streamline the design process. Drafting of the building envelope is handled by the companies themselves, while HVAC drafting, structural design, electrical drafting and life-cycle costing are done by external consultants to varying extents.

Common to all the companies is that building design and HVAC installations are performed in two phases. The building envelope is first developed and divided into modules suitable for manufacturing, followed by the detailed design where the elements building each module are drafted on manufacturing drawings. Standard CAD software for construction is used to produce the drawings. A bill of materials is produced as quantity take-off directly from drawings. Based on the bill of materials the ordering of materials is made as a manual action. There is no active process support to follow up the progress of an activity. Quality control of drawings is scheduled, but not executed.

The Manufacturing Process

The capacity of the production plants vary, where an average 150 square meters is finished modules are produced each day. Rules and limitations regarding volume assembly exist on different levels in the organisation, but are not documented with any consistent method. The rules are therefore not transparent in the design situation, and create much of the unnecessary rework between design and manufacturing.

Once the structure of the module is complete, internal cladding, painting and decoration begin. The workers use printed drawings to keep track of work tasks for a particular module. Before storing the volume, an inspection is conducted and any deviations are reported. All missing equipment or incomplete work is listed. This material is not used for any other purpose than as a memory list for ordering material or assigning labour to correct defects; there is no follow-up practice after closing the issue. Data and experience from projects are archived according to a specific project, and not related to the production process. The ownership of improvements in activities or product development does not have an appointed function.
Industrialised housing and feedback

Assembly on site

The modules are delivered to the building site by truck and their delivery times are optimised to minimise site work. The work onsite is done by small and tight groups of in-house teams and external carpenter firms. These teams move from building site to building site and have inherent knowledge about the practical aspects of the building platform. At the building site, the information flow is addressed through meetings and short instructions, but not on a regular basis. A common problem is the lack of detailed standards for a specific work task. All teams have their own solutions concerning, e.g. edging, carpet joints and doors.

Feedback initiatives

Data is organised with building projects as the base, which is natural while the project is ongoing, but difficult when the project becomes an experience. Product development is not a separate process within the companies, but rather an activity that arises from project to project. Information is dependent on individuals and no central management system controls the progress of the process; therefore, it is difficult for individuals to keep track of the project progress.

External quality audits are done on the finalised building at delivery and after a guarantee period of 2 years (mandatory in Sweden). No link exists between these audits and no model is established for traceability of quality problems backwards in the manufacturing process. Today, the action process for correcting defects is fast and non-reflective. The prevailing procedure with obvious defects, i.e. when clients demonstrate a demand for action, is to initiate immediate actions, but without follow-up of solutions. This could be described as a fire extinction approach to defects and problems.

Exploring feedback data from building inspections

Building inspections from 16 building projects and guarantee inspections from 9 projects were explored (see Table 2). Within the inspections only indoor building protocols were chosen, based on earlier studies from Sigfrid (2007), Persson (2006), and Josephson and Hammarlund (1999), implying the urgency in this area. From the investigated building inspections, 66% of defects originate mostly from factory production, followed by 21% from erection. The 11 projects from company B include 457 apartments with 7.3 defects per habitat with a maximum of 14 and minimum of 1 defects. Repairing simple defects at the building site constitutes 63% of 2,415 defects, followed by replacements at 31%, which is more severe.

Table 2: Summary of inspection protocols.

<table>
<thead>
<tr>
<th>Company</th>
<th>Projects (no.)</th>
<th>Defects (no.)</th>
<th>Modules (no.)</th>
<th>Mean value (Def./Mod.)</th>
<th>Std. dev. (%)</th>
<th>Max/min (Defects)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building inspections</td>
<td>A</td>
<td>5</td>
<td>414</td>
<td>81</td>
<td>6.1</td>
<td>66</td>
</tr>
<tr>
<td>B</td>
<td>11</td>
<td>2415</td>
<td>877</td>
<td>3.1</td>
<td>63</td>
<td>1/7</td>
</tr>
<tr>
<td>Guarantee inspections</td>
<td>A</td>
<td>5</td>
<td>66</td>
<td>81</td>
<td>1.1</td>
<td>81</td>
</tr>
<tr>
<td>B</td>
<td>4</td>
<td>424</td>
<td>828</td>
<td>0.9</td>
<td>70</td>
<td>0.3/1.6</td>
</tr>
</tbody>
</table>

DISCUSSION

Findings from the case study reveal that many of the defects occurring in newly produced houses are generated during the early stages of the construction cycle, i.e.
originating mainly from design and factory production. Little is done regarding the
use of information captured in the building inspection. The timber volume element
house manufacturer, rather than builder, is often responsible for both design and
production, giving the opportunity of seeking and promoting early design decisions
compatible with production capability. This is imperative to attain a cost effective
product, and demonstrates the contradiction between manufacturing and construction.
When manufacturing prefabricated volumes, the number of participating companies is
less, resulting in enhanced possibilities concerning learning from experience, e.g.
feedback, and thus finding connections to improvement possibilities within the
company. This in turn could present a competitive edge towards other building
systems and promote long-term quality.

The analysis of defects could give information about the most common defects, and an
opportunity to trace defects back to production and design. The purpose of building
inspections is to determine whether the contractor fulfilled what the customer has
procured. Using building inspections for evaluation, and as a bearer of information, is
not recognised by the companies.

From a Lean perspective defects represents waste. and is a way of gaining perfection,
though within the investigated manufacturers, defects are an obstacle for closing
projects. A strive for customer value is noticeable in the companies, together with a
focus on streamlining production and minimising waste. Without feedback
management it is not possible to close the Lean circle of value, pull, flow and value
stream, and reach perfection as described in Womack and Jones (2003). Sigfrid (2007)
investigated building inspections from 6 traditionally built projects and found 9.3
defects per habitat, implying that industrialised housing with 7.3 defects achieves the
same level of quality.

The investigated companies do not have a strategy for handling knowledge connected
to the correction of defects, knowledge is often connected to individuals or filed in a
specific building project. The companies in the case study are mostly sole process
owners; thus, in a learning perspective, these companies will benefit more from
organisational (company) learning (Kärnä and Junnonen 2005) as individuals, teams
and customers are more stable and thus controlled. Relations remain the same from
one project to the next.

The companies are still rooted in the construction culture without any implemented
quality culture based on a belief of continuous improvements and follow ups, as
described by e.g. Bergman and Klefsjö (2003). The construction worker is paid to
solve problems and is not instructed to stop production when serious problems occur.
The cost of not implementing a wider and deeper quality approach should be
prohibitive (Juran and Gryna 1993), but at best, one company has one person
responsible for maintaining a quality management system such as the ISO9000; this is
hardly sufficient for a €42 M turnover company.

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USA.
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Meiling and Johnsson


PAPER IV

DEFECTS IN OFF-SITE CONSTRUCTION – INDUSTRIALISED TIMBER HOUSING

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Defects in Off-Site Construction – Industrialised Timber Housing
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Abstract
The construction industry is based on craftsmanship, and a good builder is a craftsman who tackles each problem as it emerges, with consistently satisfactory results. Thus, quality control and assurance procedures applied in manufacturing (where there are high degrees of repetition, standardisation and follow-up) cannot usually be readily applied in construction, where there are higher degrees of uniqueness in each project, so responsiveness to problems and flexibility of solutions are important attributes. However, construction companies of one category (industrialised house builders) are attempting to bridge some of the gaps between construction and manufacturing. These companies prefabricate building parts for later assembly at the building site. The degree of prefabrication ranges from manufacturing open walls and floors to producing entire volume modules with complete interior cladding. Since they are wholly responsible for large parts of the building process, these companies have greater opportunities to control and improve quality in a more consistent way than ordinary construction companies. Thus, it could be hypothesised that the frequency and severity of defects should be lower in industrialised housing than in ordinary construction. The aim of the study presented here was to examine this hypothesis by measuring and characterising defects in industrialised housing. The design and manufacturing processes at two Swedish industrialised house builders has been analysed through interviews, site visits and document reviews. Here, quality audits from three phases of the building process were compiled, analysed and categorised to provide statistical measures of defects in industrialised housing. The results indicate that industrialised housing is no better or worse in terms of product quality than conventional housing. The organisation at the companies offers great possibilities for experience feedback, but this is not functioning currently. Experience feedback is essential when enhancing an industrially produced product over time. A change in company culture and leadership is needed to fully benefit from industrialisation.

Introduction
Industrialised housing in Sweden is thought to have the potential to increase efficiency and control, reduce costs and increase quality in construction (SOU 2000; Apleberger, Jonsson et al. 2007). This emerging industrialisation follows an international trend, for instance Egan (1998) argues that construction must develop into a manufacturing process. (Lessing 2006) has suggested that industrialised housing should ideally incorporate the following eight features: (1) thorough planning and control of the processes, (2) customised technical systems, (3) offsite manufacture of building parts, (4) long-term relations between contractors, (5) integration of supply chain management in the construction process, (6) strong customer focus, (7) high degree of use of information and communication technology (ICT) and (8) systematic performance measurement and use of knowledge acquired through experience. A branch of the construction industry that shows many of these eight features is industrialised house building using timber frames. The development of multi-storey, prefabricated, timber frame buildings was enabled by the introduction of functional building codes in Sweden in 1994. The degree of prefabrication ranges from manufacturing open walls and floors to producing entire volume modules with complete interior finishing.
The use of volume modules shifts 90% of the work into factories, fig. 1. (Höök 2006) states that industrialised housing changes the company culture, through standardization, from organizational learning and learning between projects, to building knowledge into the process instead of in the people, hence facilitating experience feedback.

![Figure 1 Timber volume module production and assembly](image)

Early defect studies, e.g. Schodec (1982) and Moroni and Sartori (1994), often focused on poor craftsmanship, but a more systematic approach to learning from defects has been issued by the CIB working commission W086, which is concerned with learning from building pathologies and encouraging the systematic application of acquired knowledge to building design, construction and management (CIB-W086 1993). Procedures for addressing engineering-based defects are supported by quality management systems such as ISO 9000, which can also be applied to construction (Low and Teo 2004). However, defects arise despite the application of such systems, and one reason for this is thought to be negligence (Pheng and Wee 2001). Several studies (Josephson and Hammarlund, 1999; Porteous, 1992) have also linked the occurrence of defects to the organisation and, more specifically, poor communication. Thus, organisational learning may be a key ingredient for successful application of quality management procedures (Scott and Harris 1998). However Ilozor, Okoroh et al. (2004) argue that historical analysis can also be a powerful tool, which can be combined with categorisation and systemisation of defects (Josephson and Saukkoriipi 2007). The value of reducing the frequency of defects is illustrated by calculations indicating that mistakes in construction have a major impact on production costs (Sigfrid (2007). Indeed estimates suggest that costs of correcting defects may account for up to 6% of production costs (Josephson and Hammarlund 1999), and overall costs of poor quality may be equivalent to ca. 15% of the total costs in an average building project (Josephson and Saukkoriipi 2007).

Even though buildings constructed by industrialised methods are regarded as having generally higher quality than those constructed by conventional methods, the level of chronic waste when such methods are applied (fig. 2) has not been established. Thus, it is currently impossible to judge the overall level of quality of industrialised housing. This paper presents a first attempt to quantify its quality.
The aim of this study is to characterise defects in industrialised housing and compare the findings to those of earlier studies of on-site construction, in order to assess the current quality level of industrialised construction. The study focuses on quality audits of work done by two industrialised house builders that produce prefabricated timber volume modules for the Swedish market. The two companies jointly account for 50% of the market for industrialised housing, which has a 15% share of the total market for multi-family dwellings in Sweden. Quality audits from eight different building projects were analysed and each detected defect was categorised. The grand total of assessed defects was 2713.

Timber Volume Module Prefabrication

The organisation at the two studied companies A and B is not process-oriented in any formal way. Building projects follow predefined paths involving multiple activities, fig. 3. The companies try to run everything in-house, preferably according to a design-build contract. Most activities remain in-house, although some are performed by external consultants. Company A works solely for clients who sublet dwellings to private customers, while company B works with institutions that need public buildings, e.g. schools, jails, day-care centres etc. Company A has chosen to work with their clients very early in the building process, sometimes even before building permits are granted. Company B does not have this option since public buildings are subject to European Procurement rules and thus have to be announced and open to competition. Early design decisions favouring industrialised housing are almost impossible to carry through when open bidding is applied. The timeframe of the activities following procurement is illustrated in figure 3, and the main stages of the construction process are described below.

Figure 3 Timeframe for a typical building project and activities during design, manufacturing and commissioning stages.
Briefing
The briefing period includes four weeks of early client contacts, 12 weeks to acquire the building permit, eight weeks to prepare a tender and 12 weeks for tender negotiations and acceptance. The sales department is staffed by two persons at both companies. The architectural work is conducted by either in-house or external architects who are experienced (in both cases) in the volume module prefabrication system. After sales, a start-up meeting is held in which object-specific demands are considered. The companies have assigned documentation of the technical platform as part time work. Early design work is allocated to the sales department and assigned to a skilled senior design employee, but due to capacity problems this person is often occupied elsewhere.

The Design Process
Standardisation is incorporated into the design process by defining standard joints, standard stairwells, standard wall and floor sections etc. Since the layout of the building greatly affects its manufacture, strategic alliances with architects and customers are sought to streamline the design process. Drafting of the building envelope is handled by the companies themselves, while heating, ventilation and air conditioning (HVAC) drafting, structural design, electrical drafting and life-cycle costing are done by external consultants to varying extents. Building design and HVAC installations are performed in two phases. The building envelope is first developed and divided into volume modules suitable for manufacturing. Then follows the detailed design in which the plane elements (walls, floors etc.) are drafted. Standard CAD software for construction is used to produce drawings, a bill of materials is then generated from quantities taken directly from the drawings, and used as a basis for manually ordering the required materials. However, there is no active process support to follow up the progress of any activity. Quality control of drawings is scheduled, but seldom executed.

The Manufacturing Process
On average 150 square meters of finished modules are produced every working day at each company. Volume assembly limitations are not documented by any consistent method and thus are not readily apparent during the design process. Once the structure of a module is complete, internal cladding, painting and decoration begin. The workers use printed drawings to keep track of work tasks for a particular module. Before storing the module, it is inspected, any deviations are reported and all missing equipment or incomplete work is listed. However, the resulting lists are not used for any purpose other than as notes for ordering material or assigning labour to correct defects. No one is assigned responsibility for improving activities or product development, and there are no formal procedures for fostering such improvements.

Assembly on site
The modules are delivered to the building site by truck and their delivery time is optimised to minimise site work. The work onsite is done by small, tight groups of in-house teams or external carpenters. These teams move from building site to building site and have inherent knowledge about practical aspects of the building platform. At the building site, information is channelled through meetings and brief instructions on an irregular basis. A common problem is the lack of detailed standards for specific work tasks. All teams have their own solutions concerning matters such as edging, joints and doors.

Feedback initiatives
Information regarding the companies’ products is recorded with respect to specific projects, which is logical while projects are ongoing, but less useful when the projects have finished and the information could provide useful experience-based feedback.
Further, product development is not a separate process within the companies, optimised to deliver standardised, experience-honed buildings, but rather an activity that is tackled in an *ad hoc* project-by-project manner. The flow of information to and from the designers and other staff involved in the projects is dependent on individuals, and is not subject to any central management system, so it is difficult for individuals to keep track of projects’ progress. Finalised buildings are subjected to an external quality audit at delivery and (in Sweden) another mandatory audit after a warranty period of two years. However, there is no link between these audits and no procedure has been established for tracing quality problems back in the manufacturing process to identify systematic problems. The current action process for correcting defects is fast and non-reflective. Thus, the prevailing procedure has several obvious defects, notably when clients demand action, the general response is to initiate immediate corrective measures, but without follow-up analysis of possible preventative solutions. Hence, a fire-fighting rather than fire-prevention approach to defects and problems is adopted.

**Research method**

Defects are detected at several control points in the building process. As mentioned above, in Sweden there is a mandatory final audit when a building is complete and a warranty audit after the building has been in service for two years, both conducted by external professionals (fig. 3). In addition, the studied companies apply an internal quality audit before the manufactured volume modules leave the factory. To overview the types of defects that arise in the companies’ building processes, when they occur and their causes, audits from all three control points were collected and examined. In order to assess the total waste in a process, direct observations are needed to identify defects that are corrected while the process is still underway (Josephson and Hammarlund 1999). However, in this first attempt to quantify defects in industrialised housing, only data available from the audits were analysed. Further, the analysis was restricted to a handful of projects run by companies A and B for which complete data were available (factory, final and warranty audit), table 1.

| Case Company No. of employees Main products Turnover (MEuro) Selected projects (no. of volume modules) No. of storeys Year |
|-------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| A 150       | Multi-family and student dwellings 34 | Condominiums (40 mod.) | 2 | 2004 |
|             |                               | Student dwellings (92 mod.) | 4 | 2003 |
|             |                               | Student dwellings (230 mod.) | 4 | 2003 |
| B 253       | Schools and office buildings 43 | School (11 mod.) | 1 | 2006 |
|             |                               | Hospice (19 mod.) | 1 | 2005 |
|             |                               | Preschool (16 mod.) | 1 | 2005 |
|             |                               | Preschool (28 mod.) | 1 | 2005 |
|             |                               | Preschool (7 mod.) | 1 | 2005 |

In total, 443 volume modules were included in the analysis of the quality audits. In total, across all projects, 1234 defects were detailed in the factory audits, 1147 in the final audits and 332 in the warranty audits; a grand total of 2713. Defects are recorded in reports and stored in text format in the companies’ archives. The reports were reviewed and all defects coded using six different categories; where, what, type, measure, why and when. Each category was associated with a nominal scale according to table 2, corresponding to parts of the process described by Love and Josephson (2004), in which classification, correction, roots and cost effects of defects are described. The costs of the defects are not included in table 2.
Table 2. Nominal scales for characterising defects.

<table>
<thead>
<tr>
<th>Where did the defect occur?</th>
<th>What was defective?</th>
<th>What type of defect was it?</th>
<th>What measures were taken to correct the defect?</th>
<th>Why did the defect occur (root cause)?</th>
<th>When did the defect occur?</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 Unrelated</td>
<td>0 Unrelated</td>
<td>0 Unrelated</td>
<td>0 Unrelated</td>
<td>0 Unrelated</td>
<td>0 Unrelated</td>
</tr>
<tr>
<td>1 Dwelling</td>
<td>1 Int. installations</td>
<td>1 Missing</td>
<td>1 None</td>
<td>1 Transport</td>
<td>1 Structural</td>
</tr>
<tr>
<td>2 Common areas</td>
<td>2 HVAC</td>
<td>2 Unfinished</td>
<td>2 Cleaning</td>
<td>2 Damaged</td>
<td>2 Factory</td>
</tr>
<tr>
<td>3 Separate buildings</td>
<td>3 Opening</td>
<td>3 Broken</td>
<td>3 Adjustment</td>
<td>3 Bad craftsmanship</td>
<td>3 Transport</td>
</tr>
<tr>
<td>4 Outdoors</td>
<td>4 Lining</td>
<td>4 Erroneous</td>
<td>4 Completion</td>
<td>4 Structural</td>
<td>4 Assembly</td>
</tr>
<tr>
<td>5 Wall</td>
<td>5 Wall</td>
<td>5 Repair</td>
<td>5 Exchange</td>
<td>5 Structural</td>
<td>5 Warranty time</td>
</tr>
<tr>
<td>6 Ceiling</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 Floor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 Completions</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 Information</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

The first two categories (where and when) were each divided into more detailed sub-categories, which are not presented in table 2. Every defect was coded and entered in SPSS statistical software for analysis and presentation of data in a consistent manner.

Results and statistical analysis

On average, each volume module had 6.1 (2713/443) defects, assuming all defects were corrected after detection in an audit. Volume modules made by companies A and B had, on average, 5.0 and 9.3 defects per module, respectively.

Where did the defects occur?

This question is linked to how far the building process has progressed at the time of the audit. Totals are presented in fig. 4.

Figure 4. Where did defects occur?

From fig. 4 it is clear that dwellings harness the most defects, which is not surprising since they constitute the major parts of the buildings. The higher proportion of defects in common areas recorded in the final audits (which can be seen in figure 4) is also no surprise since common areas are constructed during onsite work, and thus their frequency will inevitably rise in the final audits.’
**What was defective?**

The generic parts of the building structure were used to map the defects, fig. 5. The most frequent problems were clearly associated with walls and openings. Recorded defects include holes and mess on the walls caused by craftsmen, missing linings around doors and windows, and doors in need of adjustment due to movements in the structure. Of the grand total, 33% of all defects were related to walls, and 52% to walls or openings. Defects in interior installations emerged in the factory and final audits, and concerned objects that were missing or not properly installed. In the warranty audits malfunctions were noted. Although interior installations have little to do with the building system *per se*, the contractor is held responsible for defects in them, especially in industrialised housing where the manufacturer makes a “total offer”.

---

**Figure 5. What was defective?**

**What type of defect was it?**

The cost of correcting a defect is clearly coupled to the type of defect involved, therefore it is of obvious interest to grade the severities of the defects (as illustrated in fig. 6).
Figure 6 shows that many items were missing before delivery at the time of the factory audits (518 items in total, equivalent to 1.2 items missing/volume module, accounting for 42% of the defects recorded in these audits). Furthermore, many defects recorded in the factory audits concerned broken items (35%) that had to be corrected before the final audit. In the final audits, the lion’s share of defects concerned things that had not been delivered according to the contract (55%). On average, 79 items/project were listed as not to the customer’s satisfaction in the final audits. According to the warranty audits, some 20 items/project did not meet contract stipulations.

What measures were taken to correct the defects?

To qualitatively assess the costs of the defects for the contractor and establish another measure of the costs of correcting them, the measures taken to correct each defect were recorded (fig. 7). Figure 7 shows that most of the defects (51% of the total) were small, requiring only minor adjustments. Typical defects included stains, mess, small cracks and marks. The numbers of defects requiring repair or exchange amounted to 9.6% (260/2713) of the total. In the factory audits completion was the second most common measure to correct defects, which is unsurprising since many items were missing in that phase.
Why did the defect occur?

Most of the defects that occurred during factory production and assembly on-site were due to human error, fig. 8, in accordance with expectations in a work-intensive activity such as construction. For industrialised housing it is interesting to examine the number of defects associated with structural errors, since the structure is repeated, so structural errors affect every volume module produced. Such errors constituted 21% (578/2713) of the defects. During factory production, most structural errors are directly connected to design errors, and long-term effects on the building system only become apparent after some time in service. Typical structural errors recorded in the warranty audits included cracks in corners and movements in the structure. Structural errors constituted nearly half of all the defects listed in the warranty audits, corresponding to 6% of the grand total.

When did the defect occur?

Figure 7 Measures taken to correct defects.

Figure 8 Root causes of defects.

Figure 9 Building process stage when defects occurred.
As can be clearly seen in fig. 9, factory production is the phase in which most defects occur. Transport causes some 10% of the defects detected in the final audits, manifested in cracks in weak sections, and windows and doors in need of adjustment. Half of the defects detected in the warranty audits arose during the two years that had passed since the final audits. However, even after two years, defects either remained or had arisen that could be directly linked to errors during the factory production processes (20%) or assembly of the buildings (23%).

**Principal Component Analysis**

To analyse trends in the data and assess the possibility of summarising them in fewer (readily interpretable) dimensions than those presented in table 2, the datasets in the factory, final and warranty audits were each subjected to Principal Component Analysis (PCA). There was insufficient scatter in the factory audit data to summarise into aggregated variables, which is not surprising since several of the scales applied only allow one or two categories at the factory audit stage, e.g. “where” can only elicit the responses “0, Unrelated” or “1, Dwelling” since the other alternatives in the scale are non-existent at the time of the factory audit. Rotated component matrices for the PCAs of the final and warranty audits are presented in fig. 10.

<table>
<thead>
<tr>
<th>Component</th>
<th>Matter_3D</th>
<th>Problem_fix</th>
<th>Time_cause</th>
</tr>
</thead>
<tbody>
<tr>
<td>Where_1</td>
<td>.78</td>
<td></td>
<td></td>
</tr>
<tr>
<td>What_1</td>
<td>-.65</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Where_2</td>
<td>.54</td>
<td>.54</td>
<td></td>
</tr>
<tr>
<td>Measures</td>
<td></td>
<td>-.77</td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td></td>
<td>.83</td>
<td></td>
</tr>
<tr>
<td>Why</td>
<td></td>
<td>.71</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Component</th>
<th>Position_4D</th>
<th>Matter_cause</th>
<th>Problem_fix</th>
</tr>
</thead>
<tbody>
<tr>
<td>When</td>
<td></td>
<td>-.71</td>
<td></td>
</tr>
<tr>
<td>Where_2</td>
<td>.69</td>
<td>.77</td>
<td></td>
</tr>
<tr>
<td>Where_1</td>
<td>.58</td>
<td>.76</td>
<td>-.76</td>
</tr>
<tr>
<td>Why</td>
<td></td>
<td>.77</td>
<td></td>
</tr>
<tr>
<td>What_1</td>
<td>.76</td>
<td>.70</td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>.76</td>
<td>.70</td>
<td></td>
</tr>
<tr>
<td>Measures</td>
<td>.76</td>
<td>.70</td>
<td></td>
</tr>
</tbody>
</table>

*Figure 10 Component matrices (rotated by Varimax with Kaiser Normalization) for the Principal Component Analyses of the final and warranty audits.*

The Principal Component Analyses (PCA) show some relationships that remained consistent throughout the timeframe of the quality audits, but also some that changed with time. The first principal component (PC) obtained from the PCA of the final audits, designated “Matter_3D”, describes what was defective in combination with the positions of the defects. Accordingly, the final audits show that it is not uncommon for certain types of defects to repeatedly occur – for instance cracked corners may repeatedly occur at the same position for the same reasons. The first PC obtained from the PCA of the warranty audits, “Position_4D”, also has positional contributors, but in this case it is also related to time, which is consistent with expectations since time can only be related to defects at specific positions after some time has elapsed. Defects typically detected in the warranty audits include cracks around openings due to settlement. This type of defect can only be detected during the warranty period, since it is invisible before it. One component that arose in both analyses illustrated in fig. 10 is “Problem_fix”, which combines the defect type with the measure to correct it. This component shows that the type of defect detected and the corrective measure are closely related and could be described using just one variable, which should facilitate future analysis. The connection is also unsurprising since small defects also need small measures for
correction. To assess possible differences between companies A and B in terms of defect-related variables, scatterplots were produced, but none of them indicated any significant differences between the companies, see for instance fig. 11. No statistically significant differences between them in these respects were detected by a t-test either.

![Figure 11 Example of scatterplot from the PCA of the final audits.](image)

From fig. 11 it is evident that the scatter around zero is evenly distributed for both companies and there is no significant clustering of data or interesting outliers that requires attention to complete the analysis.

**Analysis and discussion**

The most important finding from this study is that industrialised housing appears to be currently no better or worse than ordinary construction in terms of frequencies of defects. Sigfrid (2007) investigated building inspections from six traditionally built projects and found 9.3 defects per habitat, very similar to the frequency (6.1 defects per habitat) found in the records of industrialised housing we examined. There were 5.0 and 9.3 defects per volume module produced by companies A and B, respectively. The difference between the companies in this respect may be linked to differences in their procurement procedures. Company A produces dwellings, which are not official buildings and are not subject to the European Procurement Agreement. The final and warranty audits clearly indicate that many defects are related to failure to fulfill customer demands regarding installations in the building (alarm systems, professional kitchen appliances etc.). Thus, there is great potential for improvements in the companies’ procedures for addressing these issues, which are not directly linked to the building system, but are still part of the overall package offered in industrialised housing.

Almost half of the defects recorded in the investigated final audits originated during the factory production processes, followed by 35% from assembly activities. Production in the factory is intense, and this is where attempts to optimise the work have primarily focused. Relatively little attention has been paid to the assembly phase, but this should be worthwhile, especially for company B, since many defects pertain to installations handled in the assembly
One of the major criticisms that has been raised against industrialised housebuilders (Höök 2006) concerns their choice of building system (light-weight timber frame walls and floors assembled into volume modules). One would therefore expect a substantial frequency of defects to be associated with the building system or structural design and, accordingly, 21% of the grand total of recorded defects can be directly linked to the structural design phase and/or building system. This proportion is very similar to the amount of chronic waste (20%) that Juran and Gryna (1974) found could be related to the planning of processes. These defects are of two main types: cracks in weak sections and design errors such as misplacement of doors or poor choices of material. The building system requires some modification to improve long-term performance and responses to settlement. The overall performance is satisfactory, but not excellent.

The companies currently make little use of information captured in the audits, although one of the companies in the case study applies a quality management strategy according to ISO 9000. However, it should be noted that ISO 9000 is often seen as a burden rather than a boon by small companies (Gustafsson, Klesjö et al. 2001). The industrialised house builder is responsible for both design and production, providing opportunities to seek and promote early design decisions that are compatible with production capability. This is imperative to ensure that production is cost effective, and is associated with important differences between manufacturing and construction. When manufacturing prefabricated volume modules, the supply chain is stable since there are long-term agreements, ICT tools provide templates for repetitive work, the modules are produced off-site in factories, and defects are traceable through internal quality control and inherent knowledge. Altogether, several key ingredients required to promote and exploit experience feedback are present, which could provide a competitive edge with respect to other building systems and promote long-term quality. However, methods need to be introduced to standardise experience capture and, more importantly, implement knowledge gained through experience in earlier process stages. This problem has been addressed in several studies, e.g. Shelbourn, Bouchlaghem et al. (2006) and Sandberg, Johnsson et al. (2008), but no simple, robust way of tackling it has been implemented as yet.

The companies in the case study are almost entirely sole process owners. Thus, these companies could benefit more from applying organisational (company) learning (Kärnä and Junnonen 2005) than conventional construction companies, since the individuals, teams, customers and relationships involved in their projects are more constant and controlled. The companies are still rooted in the construction culture, without any implemented quality culture based on a belief in continuous improvements and follow ups, as described for instance by Bergman and Klesjö (2002). ISO 9000 has been implemented at one of the companies in order to satisfy customers, rather than to improve company performance. The construction worker is paid to solve problems and is not instructed to stop production when serious problems occur. Industrialised house builders have the potential to take full advantage of quality management, but they need to shift focus from project-based to process-based production (Winch 2006).

Acknowledgements

Financial support from the Swedish Governmental Agency for Innovation Systems, VINNOVA and the participating companies in the study, is gratefully acknowledged. This work was performed within the competence centre Lean Wood Engineering and with support from the SkeWood programme.
References


Appendices

Appendix 1  Tennant questionnaire
Appendix 2  Stairwell inspection and grading
Appendix 3  Interview form
Appendix 4  Chosen habitats for stairwell investigation
BRUKARUNDESSÖKNING TRAPPHUSS


1. Jag har bott i den nuvarande lägenheten i ca: ______ år
2. Jag bor på våning: bv 1tr 2tr 3tr 4tr 5tr 6tr 7tr
3. Det finns hiss i mitt bostadshus: Ja Nej

4. Vad tycker du om följande egenskaper i ert trapphus: 

<table>
<thead>
<tr>
<th>A) Utseendet på ert trapphus?</th>
<th>Mycket dåligt</th>
<th>Mycket bra</th>
<th>Vet inte</th>
</tr>
</thead>
<tbody>
<tr>
<td>B) Bredden på trapporna?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C) Materialet som trapporna är tillverkade i?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D) Skicket på trapporna i trapphuset?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E) Trappornas upplevda stabilitet?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F) Belysningen i trapphuset?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G) Trapphusets städning?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H) Luftkvalitet i trapphuset?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I) Färgsättningen av trapphuset?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J) Avstållningsytor på entréplanet?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K) Känslan av rymd i trapphuset?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L) Utseendet på entrén?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M) Skicket på golvet i trapphuset?</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5. Vilka känslor får du när du kommer in och tittar dig runt i ert trapphus? 

<table>
<thead>
<tr>
<th>Negativa</th>
<th>Mycket positiva</th>
<th>Vet inte</th>
</tr>
</thead>
</table>

1/4
Kontaktperson: John Meiling  
johmei@ltu.se

6. Hur tycker du att det går att:

a) gå i ert trapphus? ........................................  

b) möta en person i en trappa i ert trapphus?....  
c) flytta stora möbler i ert trapphus?.............

7. Vad tycker du om ljudnivån:

a) från trapphuset in till er lägenhet? ..............  
b) när du vistas i ert trapphus? ........................

8. Skulle du vilja att ert trapphus var mer påkostat?

Ja  Nej  Vet inte

9 a) Känner du dig trygg att vistas i ert trapphus?

Ja  Nej  Vet inte

b) Om Nej, varför inte?

_______________________________________

10 a) Vilket material är trapporna i ert hus tillverkade i?

Betong  Stål  Trä  Annat  Vet inte

b) Vilket material skulle du vilja att trapporna i ert trapphus var tillverkade i?

Betong  Stål  Trä  Annat  Vet inte

c) Varför?

_______________________________________

11. Vad skulle du vilja förbättra med ert trapphus?

_______________________________________

_______________________________________

_______________________________________
12. Hur viktigt tycker du det är att ett trapphus är konstruerat så att det:

<table>
<thead>
<tr>
<th></th>
<th>Inte alls viktigt</th>
<th>Mycket viktigt</th>
<th>Vet inte</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) är snyggt?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b) har fönster (glaspartier) utåt?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>c) behåller ett fint skick år efter år?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>d) är lätt att hålla rent?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>e) känns stabilt att gå i?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>f) är lätt att gå i?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>g) inte har en störande ljudnivå?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>h) har breda trappor?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>i) går lätt att flytta stora möbler?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>j) går lätt att mötas i trapporna?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>k) finns balkoner på vill- eller vånings-planen?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>l) har bra belysning?</td>
<td></td>
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</tr>
<tr>
<td>m) går att gå snabbt i trapporna?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>n) har fin färgsättning?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>o) inte snabbt blir slitit i ytskikten?</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>p) känns rymligt?</td>
<td></td>
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<tr>
<td>q) finns vilplan mellan våningsplanen?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>r) finns avställningsytor på entréplanet?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>s) har bra luftkvalitet?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>t) finns en snygg entré till bostadshuset?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>u) känns tryggt att vistas i?</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

VÄNDI
13. a) Vilken typ av trappa föredrar du?

14. Vad tycker du är viktigast med ett trapphus?

15. Vad tycker du representerar ett snyggt trapphus?

Fyll i e-post adress eller telefonnummer om du vill ha chansen att vinna 10 biobiljetter:

Tack för att du tog dig tid att fylla i enkäten!
Kom ihåg att lämna den i lådan i entrén.
### TRÅTRAPPOR

<table>
<thead>
<tr>
<th></th>
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<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Stad och bygår 1/2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bygår 1/2 (Trätrappor) 1994</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bräckeg. 1-5 och Kirunag. 16-20</td>
<td>5</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Vällingby</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Sprickor i fjog mellan vagnstcke och vägg, lite småskador på vagnstcke, syns inte så mycket eftersom de är målade i en förlåtande färg. Linoleummatton i bra skick, trapploppet är placerat längst in i trapphuset.</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>4,6</td>
<td>3</td>
<td>4</td>
<td>4,5</td>
</tr>
<tr>
<td>Drottning Kristinas väg 69-73, Stockholm</td>
<td>5,5</td>
<td>-</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>1,9</td>
</tr>
<tr>
<td>Planstegen och sättstegen är fläckiga där människor har gått. Linoleummatton är repig och noslisten sliten. Under sidan var smutsig. Trappen hade tidigare rasat ca 1 decimeter.</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3,4</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Helgessons väg 12, Nacka</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3,8</td>
</tr>
<tr>
<td>Trappan är smutsig, framförallt på planstegen, det finns några få men stora fläckar på vagnstcke och räcke.</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>5</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Kungshamra, Solna</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2,9</td>
</tr>
<tr>
<td>Repig gummimatta i gånglinjen. Märken och fläckar på vagnstcke och sättsteg. Rätt smutsig trapp.</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>2,8</td>
<td>3</td>
</tr>
<tr>
<td>Norrbodavägen 7,17, Kungsängen</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2,9</td>
</tr>
<tr>
<td>Små rispor i gummimattan, småmärken i vagnstcke och räcke och sprickor på undersida trapp.</td>
<td>4</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>3,4</td>
<td>3</td>
</tr>
<tr>
<td>Papegojvägen, Västerås</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3,1</td>
</tr>
<tr>
<td>Linoleummatton är sliten där man går, småmärken i vagnstcke.</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Roslagstullsbacken 39, Stockholm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4,3</td>
</tr>
<tr>
<td>Väl-installerad trappa med bra passform men med fläckiga plansteg, i övrigt i gott skick.</td>
<td>1</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Vallgränd, Haninge</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4,3</td>
</tr>
<tr>
<td>Sliet linoleummatto på plansteget, slitet sättsteg, sliet vagnstcke framförallt mellan bottenvåning och 1:a våning. Slietaget kan bero på att trappan används mycket eftersom hissen är långsam.</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>2,0</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Vänortsvägen 2-22, Luleå (Tråtrappor)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2,7</td>
</tr>
<tr>
<td>Mycket sliten linoleummatto, helt genomnött ytsikt på flera ställen. Sparkmärken i sättstegen. Övriga trappdelar i godkänt skick.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>2,6</td>
<td>3</td>
</tr>
</tbody>
</table>
**BETONGTRAPPOR**

<table>
<thead>
<tr>
<th>Bra</th>
<th>Dåligt</th>
<th>Varken bra eller dåligt</th>
<th>Mycket bra</th>
<th>Mycket dåligt</th>
</tr>
</thead>
</table>

**Emmylundsvägen 5, Solna**

Planstegen och sättstegen är fläckiga där människor har gått. Inågra plansteg finns sprickor, trappen har i övrigt få märken.

![Score](2004 4 3 - 4 4 3,8 3 2 3 2,9)

**Jönåkersvägen 2, Enskede**

Slarvigt uppförd trapp, med många lagningar. Det slitage som kommer från trappanvändninga är fläckiga plan och sättsteg. Betongen har även blivit repig

![Score](2006 3 3 2 2 2 2,4 2 3 4 2,5)

**Vänortsvägen 22, Luleå (Betontrappor)**

Mycket bra skick på stegen i terrazzo. Handledarna är i ett stycke och ser nya ut. En större spricka på undersida av trapp.

![Score](1994-96 4 5 - 4 5 4,5 3 3 4 3,5)

**STÅLTRAPPOR**

<table>
<thead>
<tr>
<th>Bra</th>
<th>Dåligt</th>
<th>Varken bra eller dåligt</th>
<th>Mycket bra</th>
<th>Mycket dåligt</th>
</tr>
</thead>
</table>

**Lilla malmtorp, Vårsta**

Stålframkanten på plansteget är slit, trappan är slarvigt rengjord efter klinkerläggning.

Klinket är i bra skick

![Score](2002 3 - 4 4 5 4,0 3 3 4 3,3)

**Ärvingevägen, Kista**

Plastmatton på plansteget är i bra skick, de andra delarna likaså. Undersidan är smutsig

![Score](2002 4 - 4 3 4 3,8 3 4 2 3,6)

---

BETYG: 1 = Mycket dåligt 2 = Dåligt 3 = Varken bra eller dåligt 4 = Bra 5 = Mycket bra
Syftet med denna undersökning är att ta reda på vad du och andra som sköter om trapphus tycker är viktigt med ett trapphus.

1. Vad tycker du är viktigast med ett trapphus ur ett underhållsperspektiv?

______________________________________________________________________

2a. Föredrar du trätrappor, ståltrappor eller betongtrappor?

b. Varför

______________________________________________________________________

3a. Vilket golvmaterial tycker du är bäst i en trappa? (linoleum, plast, terazzo, klinker, mm)

______________________________________________________________________

b. Varför

______________________________________________________________________

4. Vad tycker du representerar ett riktigt bra trapphus?

______________________________________________________________________

5a. Vilken typ av trappa föredrar du?

b. Varför

______________________________________________________________________
1. Bräckeg. 1-5 och Kirunag. 16-20, Vällingby (Kanslisilket) (Hyreslägenheter)

2. Drottning Kristinas väg 69-73, Stockholm (Studentlägenheter)

3. Emmylundsvägen 5, Solna (Pax) (Studentlägenheter)

4. Helgessons väg 12, Nacka (Trigonen) (Studentlägenheter)

5. Jönäkersvägen 2, Enskede (Hyrslag)

6. Papegojvägen, Västerås (Studentlägenheter)

7. Norrbodavägen 7,17, Kungsängen (Bostadsrätter)

8. Roslagstullsbacken 39,41 (Studentlägenheter)

9. Vallagränd, Haninge (Kandidaten etapp 1) (Studentlägenheter)
Klinker i entré, linoleummatta på våningsplanen. Ett fönster på varje våningsplan. Lackad trätrapp med stålträ och träledare på stället. Ett enklare hiss.

10. Vänortsvägen 2-22, Luleå (Studentlägenheter)
Linoleumgolv på våningsplanen. Rosa väggar från golvet till mitten på vägg sedan vita. 2 och 12 har betongtrappor och de andra numren har trätrappor. Alla trappor har räcke i trä. His in de hus med 4 våningar.

11. Kungshamra, Solna (Kandidaten etapp 1) (Studentlägenheter)
Klinker i entré, linoleummatta på våningsplanen. Ett fönster på varje våningsplan. Lackad trätrapp med stålträ och träledare på stället. Ett enklare hiss.

12. Dalvägen, Värsta (Lilla Malmtorp) (Bostadshus)
Klinker i entré, linoleummatta på våningsplanen. Ett fönster på varje våningsplan. Lackad trätrapp med stålträ och träledare på stället. Ett enklare hiss.

13. Årvingevägen 14-16, Kista (Gedser) (Studentlägenheter)
Entré med PVC-matta på golvet, ljusblå väggar. Fönster i trapphus med 2-vånings takhöjd, upplevs rymligt, Riktiga krukväxter. Svart trätrapp med träledare, klinker i trapp.
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