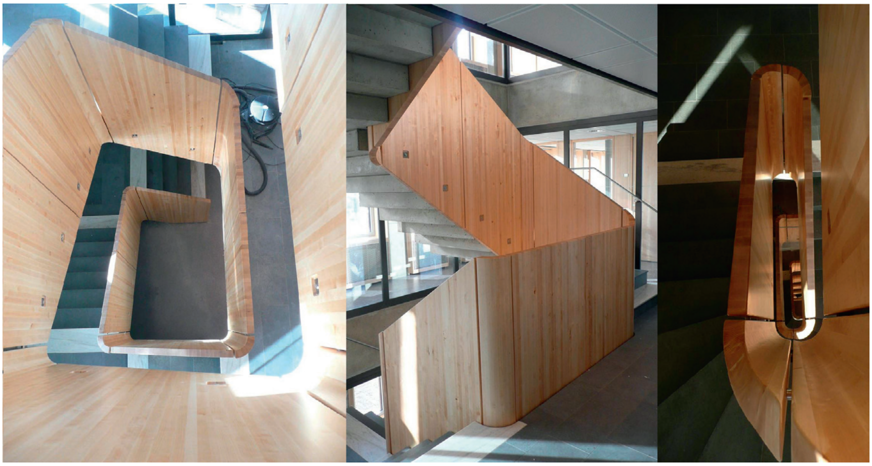
LICENTIATE THESIS

Supplying Engineer-to-Order Joinery Products to the Construction Industry



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LULEÅ UNIVERSITY OF TECHNOLOGY

Licentiate Thesis

Supplying Engineer-to-Order Joinery Products to the Construction Industry

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Preface

This work has been performed at the Wood Technology division of Luleå University of Technology, Department of Engineering Sciences and Mathematics, under the supervision of Professor Anders Grönlund and Dr Micael Öhman.
The work has been funded through the European Union Objective 2 programme "*Marknadsstyrd flexibel trämanufaktur*" (*Market Driven and Flexible Wood Manufacturing*) and the Swedish Governmental Agency for Innovation Systems, Vinnova. This is gratefully acknowledged.

I wish to acknowledge the numerous people, companies, and organizations that have made this research possible, especially the industry partners within the EU Objective 2 programme. In no particular order, I would like to personally thank the following industry representatives for their contributions in terms of time, effort, and knowledge sharing: Peter Forsell, Johan Bodén, Åke Hallberg, Anders Åström, Per Enarsson, Clas-Göran Färnqvist, and Peter Wallinder.

The interview respondents in this research have been an invaluable asset in sharing their experiences and knowledge. You are all gratefully acknowledged.

This is a halfway stop at the journey towards a PhD. As is the way with interesting journeys, the road isn't always straight, and when you least expect it you find glimpses of life. The co-authors of my work and my collegial training team have contributed to those moments in this journey and are greatly acknowledged.

Finally, I would like to thank: my family and friends for their love, comfort, and fun; my father and mother for support and encouragement in pursuing my life's dream in Kittelfjäll; my dear children Lukas and Alice, you give me such joy and comfort; Sofia, for the moments we have had that I will keep in my heart, thank You; and "Stojje" for all the fun things to do with you.

Skellefteå, May 2012

Samuel Forsman

Abstract

The supplying of engineer-to-order joinery products to the construction industry is considered a novel research area in the wood-related literature as well as in the construction-related literature. The process of supplying the construction industry with highly refined one-of-a-kind wood products is examined in this thesis, and more specifically, an organization using a mixture of concept-to-order and design-to-order production strategies to produce Engineer-to-order Joinery Products. The focus in this work is on the possibilities for innovation in the industry of supplying engineer-to-order joinery products and on improved integration with the construction industry.

The construction industry has been criticized for not keeping up with other production industries in terms of quality, cost efficiency, innovation, and production methods. The development of Lean production principles and supply chain management are innovations commonly suggested as improvements in increasing the degree of industrialization to the construction industry, and this is also reflected in this work where waste in the process has been identified.

The work is weighted towards a qualitative research approach, and real-world case studies have been used for the empirical data collection.

Results from the studied cases indicate that the process of supplying engineer-to-order joinery products to construction has the potential for improved efficiency. Violations of Lean principles are identified, and these have effects on the process of supplying joinery products to construction. Much of the identified waste can find its cause in these violations. Innovation in adopting Lean principles and managing information, supply chain, planning, and coordination is believed to be essential for improving total process performance in supplying engineer-to-order joinery products to construction.

The supplying of engineer-to-order joinery products faces opportunities and challenges similar to those in the industrialized housing industry. An increased level of prefabrication, decreased assembly time, and increased predictability of on-site work seem possible if confronting the root causes found in this work.

Sammanfattning

Processen att leverera snickeriprodukter som designas och utvecklas mot kundorder (Engineer-to-Order) kan betraktas som ett nytt forskningsområde inom såväl träforskningen som inom byggrelaterad forskning. I denna avhandling har processen att leverera högt förädlade "One-of-a-Kind" träprodukter studerats och mer specifikt en organisation som använder sig av produktionsstrategierna "Concept-to-Order" och "Design-to-Order" för att producera sina snickeriprodukter. Arbetet fokuserar på möjligheterna till innovation inom denna industri samt en förbättrad integration till byggindustrin som är dess huvudsakliga avnämare.

Byggindustrin har kritiserats för att inte hålla jämna steg med andra tillverkningsindustrier när man ser till kvalitet, kostnadseffektivitet, innovation, och produktionsmetoder. Utveckling av tillämpandet av principerna för Lean Production och Supply Chain Management är innovationer som ofta föreslås för att öka graden av industrialisering i byggbranschen. Detta återspeglas också i detta arbete där resursslöserier har identifierats utifrån principerna för Lean Production och Supply Chain Management. Arbetet har till övervägande del haft en kvalitativ forskningsapproach och fallstudier från verkliga fall i den studerade industrin har använts för att samla in det empiriska materialet.

Resultaten från de studerade fallen indikerar att processen att leverera Engineer-to-Order snickeriprodukter till byggindustrin har potential att utveckla effektiviteten med tillgängliga produktionsmetoder och teknikutnyttjande. De överträdelser mot principerna inom Lean som hittats anses ha effekter på verkningsgraden i processen att leverera denna typ av snickeriprodukter till byggindustrin. Mycket av det identifierade resursslöseriet har sin orsak i dessa principöverträdelser. Innovationer inom antagande av principerna inom Lean och ett förbättrat management av informationsflöden, Supply Chain, projekt- och produktionsstyrning, samordning/koordination internt såväl som externt mot byggprocessen anses vara väsentliga för att förbättra hela processen med att leverera Engineer-to-Order snickeriprodukter till byggindustrin.

Att leverera dessa snickeriprodukter till byggindustrin möter möjligheter och utmaningar som liknar dem som beskrivs inom det industrialiserade byggandet. En ökad grad av prefabricering, minskad monteringstid och ökad förutsägbarhet i processen, särskilt vid arbetet på byggarbetsplatsen tycks vara möjliga om de rotorsaker till problem som beskrivits i detta arbeta konfronteras.

List of Papers

Forsman Samuel, Bystedt Anders, Öhman Micael (2011)
Interaction in the construction process: System effects for a joinery products supplier
Lean Construction Journal*, 2011*, 01–18.

Forsman Samuel, Björngrim Niclas, Bystedt Anders,
Laitila Lars, Bomark Peter, Öhman Micael (2012)
Need for Innovation in Supplying Engineer-to-Order Joinery Products to Construction
Submitted to: Construction Innovation – Recommended for publishing

Laitila Lars, Björngrim Niclas, Forsman Samuel,
Bomark Peter, Öhman Micael, Hagman Olle (2012)
3-D As-Built Spatial Verification in Supplying Engineer-to-Order Joinery Products to Construction
Submitted to: *Automation in Construction*

Contents

1 Introduction

In this chapter the research presented in this thesis is introduced. First, a background to the motivation of the research is given, and then the purpose, objectives, and demarcations defining the research are presented. Finally, the disposition of the thesis is outlined.

1.1 Background

Traditionally, joinery product suppliers design and manufacture products (hardware) such as windows, doors, stairs, entrances, interiors, and kitchens. The distribution of these products can be roughly divided into two different flows: 1) One value stream consists of standardized, line-produced products that are distributed through furniture stores, office furniture stores, builders' merchants etc. Through these distribution channels the joinery products reach the smaller construction contractors, craftsmen, and the individual persons who are the end customers, or close to the end customers, of those products. 2) The second value stream, which is the focus of this thesis, supplies the construction industry with tailored, one-of-a-kind products that are fitted into a given building object. The process of the second value stream is adapted to the culture in the construction industry and has not been able to fully utilize industrialized processes in terms of cost efficiency, innovation, and production methods. Thus, this resembles the situation in the construction industry.

In media as well as in the research community the current state of construction is debated. The Swedish construction industry has been criticized for not keeping up with other production industries in terms of quality, cost efficiency, innovation, and production methods. Innovations that decrease the cost of building production and alterations have gained much attention due to their effect on the costs of living and working environments (Brege, Johansson, & Pihlqvist, 2004; SOU, 2002; SOU, 2009).

In several publications as well as within the Swedish construction industry, increased industrialization is mentioned as one possible approach to solving some of the issues found in construction, especially for residential house building (Björnfot & Stehn, 2004; Boverket, 2006; Platen, 2009). A proposed definition of industrialized house building is: *"Industrialized house-building is a thoroughly developed building process with a well-suited organization 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"* (Lessing, 2006).

The application of industrialization as a solution to the problems of construction has not only been discussed in Sweden. Industrialization in construction has also been investigated internationally in attempting to reduce non-value-adding craft-based activities and speed up the construction process with enhanced quality (Koskela, 2003; Nadim & Goulding, 2010). Industrialization seems to be a possible solution to reduce the large amount of waste in construction, even if a systems approach is needed. For this purpose, construction researchers have directed attention towards the manufacturing industry in an attempt to learn and adapt, or in some cases even copy, successful concepts (Andrew, 1998; Gann, 1996).

However, the main market for one-of-a-kind joinery products is currently not in the residential house building sector of the construction industry, but in non-residential construction projects that often can be characterized as a more traditional construction set-up and include both new and alteration construction projects. The traditional construction process has been characterized by one-of-a-kind project-based, site-based, temporary organizations, and as being fragmented in nature with loosely coupled actors who only take part in some of the phases of the process (Anheim, 2001; Vrijhoef & Koskela, 2005). However, joinery products are usually manufactured off-site with a final assembly on the construction site which resembles the prefabrication of structural elements used in industrialized house-building.

Supplying to construction

The majority of efficiency problems in construction have been shown to relate to supply chain management. Repeated suggestions have been proposed to control the supply chain as an integrated value-generating flow, rather than only as a series of individual activities, but only a few have a track record of consequent and significant success (Vrijhoef, Koskela, & Howell, 2001).

Traditionally, the price has been the dominating criterion for supplier selection in the construction industry (Jarnbring, 1994; Wegelius-Lehtonen, 1995). Furthermore, construction companies work in a culture of hiding experience and information instead of sharing them, and this culture works against effective development (Polesie, Frödell, & Josephson, 2009). It has been stressed that due to the contractual nature of the industry it is common for each party to seek to mitigate its own costs and risks by passing them on down the supply chain, which is seen to have a hampering influence on innovation in construction (Aouad, Ozorhon, & Abbott, 2010). Therefore, it is recommended that managers in construction realize that establishing a cost-effective and responsive network of suppliers is needed to succeed in providing customers with products cheaper and faster than the competitors (Nasr-Eddine Dahel, 2003).

There are examples of studies of the supply-chain management in construction (SCMC) focusing on pre-engineered metal building manufacturing, electrical switchgear, elevators, and aluminium windows (Akel, Tommelein, Boyers, Walsh, & Hershauer, 2001; Arbulu & Tommelein, 2002; Azambuja & Formoso, 2003; Elfving et al., 2002; Fontanini & Picchi, 2004). However, studies of the supply of one-of-a-kind joinery products to the construction industry are rather limited. One example though, is a Brazilian study on the supply chain of prefabricated wooden doors, which concludes that information deficiencies and a lack of integration in the system can take away the benefits of prefabrication of joinery products (Melo & Alves, 2010). Furthermore, the authors conclude that a lack of trust and preconditions results in longer lead times.

Supplying ETO joinery products

The process of supplying the construction industry with highly refined one-of-a-kind joinery products is in the focus of this thesis, and more specifically, an organization using a mixture of concept-to-order and design-to-order (Winch, 2003) production strategies. This strategy means that engineering is required in the supply of these joinery products, and consequently these are considered as engineer-to-order (ETO) products. Here, engineer-to-order refers to uniquely designed products being engineered to fit specific needs. Henceforth ETO joinery products are referred to simply as joinery products.

The joinery products supplier offers products such as entrances, glass partitions, doors, windows, furniture, cabinet fittings, special fittings, and stairs, and the supplier undertaking normally includes assembly of the product on the construction site. Generally, these products are ordered by a construction contractor but are often prescribed by an architect. Joinery products are more prefabricated than general on-site construction work, but there are still limitations on the prefabrication level in the supplying of joinery products.

The focus in this work is on the possibilities for innovation in the joinery products industry and on improved integration with the construction industry.

1.2 Purpose and objective

With this background, the purpose of this thesis is to contribute to knowledge about what hampers efficiency in supplying joinery products to the construction process. The objective is to identify the main contributors to inefficiency and to define areas for innovation to improve this industry. Much attention is given to Lean principles and their use in construction.

The research questions form the basis for selecting a research strategy (Yin, 2003). Miles & Huberman (1994) advocate dividing the objective into questions for easier delimitation of the appropriate theoretical and empirical conceptual framework for the research project. Here the objective is divided into the following research questions:

- How are joinery products supplied to construction (i.e., by what process)?
- How is the supply-chain relation between a joinery products supplier and the construction process arranged?
- How do the actors in the supply chain interact with each other?
- How can current technology for spatial measuring support the process of supplying joinery products to construction?

To answer these *how* questions, case studies are performed and the empirical data are analysed to answer the following *what* and *why* questions:

- What deficiencies can be seen from a supply-chain and information-management perspective?
- What waste is evident in the process of supplying joinery products?
- Why do this waste and deficiencies arise, and what is causing this waste?

By answering these questions, this thesis aims to contribute to a foundation for the work of answering the following research question:

- How to innovate the process of supplying joinery products to construction

1.3 Demarcations

This is applied research focusing on the development of the sector for supplying joinery products to construction. The industry of supplying joinery products to the construction industry has limited representation in research literature and is considered a novel research area.

However, in construction-related research one can find applicable theories for supplying engineer-to-order joinery products to construction. The literature studies are limited to theories for supply-chain management, information management, Lean production, Lean construction, and 3-D modelling and measuring.

This thesis considers the overall process of supplying joinery products to construction, though with limited detail in all aspects. The focus is on the interaction with the construction process and on efficiency restraints surfacing late in the process, such as in the assembly. The search for the cause of these restraints focuses on the value stream.

The study is limited to contribute to the general knowledge by determining the perceived and observed problems in the studied cases in relation to the knowledge gained in the literature studies. The study was conducted in one organizational network of joinery production companies with a co-owned sales company, which limits the possibilities for a theoretical generalisation. The study features two cases with different production units and is performed from a sub-supplier perspective; therefore, the reasons for the procurer behaviour have not been investigated.

The study shows Swedish cases and thus represents that specific cultural situation. Despite this limitation, many of the examples found in research literature globally seem applicable also to the Swedish construction culture.

1.4 Thesis Disposition

The thesis consists of two parts: the first part is the cover paper, including Chapters 1–4 listed below, and the second part comprises three appended papers described in the following chapter. The content of the cover paper is:

Chapter 1: Introduces the reader to the research field, presents the motives, aim, and research questions, and guides the reader through the disposition of the thesis

Chapter 2: Describes the chosen research methodology and the different data collection methods used

Chapter 3: Presents empirical results and discusses findings from the appended papers and additional findings from the research project; presents a cross analysis in relation to the appended papers

Chapter 4: Concludes the findings related to the aim, provides answers to the research questions in Chapter 1

Chapter 5: Gives suggestions for future research

1.5 Appended papers

Paper 1: **Interaction in the construction process: System effects for a joinery products supplier**
Written by Samuel Forsman (SF), Anders Bystedt (AB), Micael Öhman (MÖ), and published in Lean Construction Journal, 2011 issue, pp1–18. SF's contribution was to plan, perform, and analyse the interview study along with the literature study. The paper was written and the final analysis was performed by SF and AB, with feedback and critical response from supervisor MÖ.

Paper 2: **Need for Innovation in Supplying Engineer-to-Order Joinery Products to Construction**
Written by Samuel Forsman, Niclas Björngrim, Anders Bystedt, Lars Laitila, Peter Bomark, and Micael Öhman, and submitted to Construction Innovation on 2011-12-02. The contribution of SF was to plan, perform, and analyse the interview study along with major parts of the literature study. The majority of the paper was written by SF with contributions from co-authors in the Information Modelling and Method chapters. The final analysis was performed by SF and the co-authors, with feedback and critical response from supervisor MÖ.

Paper 3: **3-D As-Built Spatial Verification in Supplying Engineer-to-Order Joinery Products to Construction**
Written by Lars Laitila, Niclas Björngrim, Samuel Forsman, Peter Bomark, Micael Öhman, and Olle Hagman, and submitted to Automation in Construction on 2012-04-26. The contribution of SF, in cooperation with the co-authors, was to plan, perform, and analyse studies of 3-D measuring technology usable in the case study. The selected technology was used in a case study. SF contributed to the planning and execution of the case experiments as well as the analysis of the results.
SF also contributed to the overall design of the paper, and specifically the part with the coordinate measuring machine. The final analysis was performed by SF and the co-authors, with feedback and critical response from supervisors MÖ and OH.

2 Method

In this chapter the research process is described by presenting the methods and applied analytical approaches used when retrieving and analysing empirical data. A description of the practical process and an overall reflection are presented together with the considerations and choices made during the research process. As the main method used in this work has been working with qualitative methods, the researcher is an important instrument; therefore, the researcher's background is presented. Finally, a discussion of validity and reliability is presented.

2.1 Research approach

When confronting the aim of improving efficiency in supplying joinery products to construction, the researcher's knowledge of the characteristics of this industry was limited and this area of research was new to the division. Further it was difficult to find representation of this type of industry in literature and in the research community. Through contacts with industry representatives of Swedish joinery products suppliers, the researcher became aware that the absence of highly accurate as-built spatial information was a major restraint for efficient supply of joinery products to construction. At the research division it was thought that the current level of prefabrication could be improved if 3-D spatial information were digitalized and 3-D CAD models made to represent the true adjacent environment for the joinery products, and that this information could be used in the design and production of the joinery products. Based on this idea, a coordinate measuring machine was obtained that was able to perform geometrical measurements in three dimensions and to export this information to CAD software; therefore, the first approach was to validate this idea with the use of this machine. It was assumed that being able to digitize as-built spatial information and model this information in CAD software, and possibly control numerically controlled production machines, would have a positive impact on the efficiency of supplying joinery products to construction.

At the start, a quantitative approach was taken to validate the performance of the coordinate measuring machine. Later, cases were established to gain experience of performing spatial measuring with the machine and of the process of supplying joinery products to construction. This was done in cooperation with a major Swedish joinery products supplier who supplied the researcher with "real world" cases (Robson, 2002) that needed special attention in the spatial as-built verification before production. As the process continued, it became clear that it wasn't easy to validate the performance and that a number of factors affected the accuracy of the measurements in "real world" cases. Furthermore, to be able to validate the possible effects of such measuring equipment on the processes of supplying joinery products, more understanding of the process of supplying joinery products to construction was required. It was realized that interviews were needed to gain further understanding, and therefore a change to a more qualitative approach was necessary to enhance the understanding of the premise for supplying joinery products to construction and for using digital as-built spatial information to support this process. An exploration of the qualitative field of research was needed to deal with the *how* and *why* research questions. Therefore, support from research colleagues with more qualitative experience was garnered to jointly explore how to approach this area of research, and this resulted in co-writing of the first two appended papers.

When studying a phenomenon in its natural context, targeting rich descriptions of the phenomenon and its underlying or ambiguous elements, qualitative methods are considered suitable (Miles & Huberman, 1994). In qualitative research, the idea is often to understand a phenomenon and to generate theory from data, in contrast to quantitative research where generalizable statistics are desired. In Table 1 the differences between the quantitative and the qualitative approaches are displayed.

Table 1: Quantitative and qualitative research strategies (adapted from Bryman & Bell, 2007, p. 28)

	Quantitative	**Qualitative**
Role of Theory Approach	Deductive	Inductive
Epistemology Theory of knowledge	Positivism, natural science, explaining	Interpretivism, hermeneutic, social science, understanding
Ontology Theory of reality	Objectivism	Constructivism
Result	Verification of theory or hypothesis	Generation of theory and model

From Table 1 it can be seen that these quantitative and qualitative paradigms have different natures and views on knowledge and reality; for example, the epistemology debate whether the social world should be studied according to the same principles, procedures, and ethos as the natural sciences (positivistic view) or should require a different logic of research procedure that reflects the distinctiveness of humans, where interpretive understanding of the social action is searched in order to casually explain its cause and effect (interpretivism) (Bryman & Bell, 2007). Furthermore, the quantitative and qualitative approaches differ in their views on whether social entities can be considered objective entities that have a reality external to their social actors (objectivism), or whether they should be considered as social constructions built up from the perceptions and actions of their social actors (Bryman & Bell, 2007).

A combination of qualitative and quantitative approaches has been advocated, i.e., defining issues in the research area using a qualitative approach and then, when the area is more defined, moving on to a quantitative approach (Casebeer & Verhoef, 1997). This reflects the research path in this thesis. Here qualitative methods dominate but start to reach areas of a more narrow nature where more quantitative research applies. Furthermore, the approach can be described as abductive (Figure 1) rather than purely deductive or inductive.

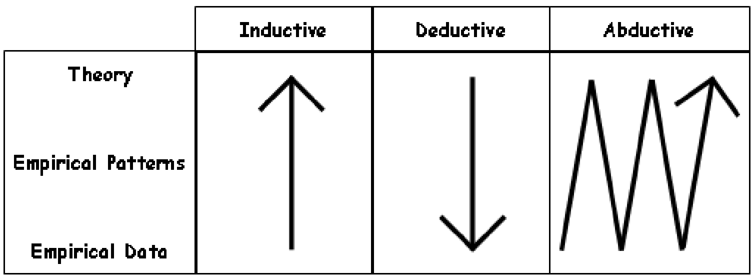

Figure 1: Research approaches (Nordvik, 2008, adapted from Alvesson & Sköldberg, 2000)

The abductive approach goes back and forth between empirical data and theory, enabling the researcher to expand the understanding of both the theory and the empirical phenomena (Dubois & Gadde, 2002). This reflects the research in this thesis, since the empirical material is examined with an open mind in the beginning and then analysed against appropriate theory; when more theoretical enlightenment is attained, the empirical context is once again approached. Furthermore, the study uses a system approach, meaning that individual parts of the studied processes are not seen as separate occurrences but as a chain of events causing a particular behaviour (Figure 2). The whole is more (or less) than the sum of its parts (Arbnor & Bjerke, 2009).

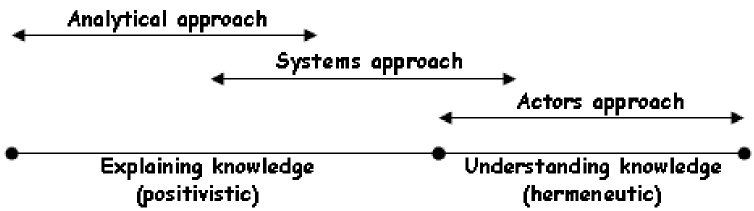

Figure 2: The different objectives of the methodological methods (Adapted from Arbnor & Bjerke, 2009)

Yin (2003) maintains that the nature of the research project determines which strategy is most suitable. The type of research question posed, the extent of the investigator's control over actual behavioural events, and the degree of focus on contemporary events determine the selection of strategy.

Table 2: Form and purpose of research questions (Based on Yin, 2003)

Research Question	Form	Purpose
How are joinery products supplied to construction?	How	Exploratory
How is the supply-chain relation between a joinery products supplier and the construction process arranged?	How	Exploratory
How do the actors in the supply chain interact with each other?	How	Exploratory
What deficiencies can be seen from a supply-chain and information-management perspective?	What, with an underlying "why"	Explanatory
What waste is evident in the process of supplying joinery products?	What, with an underlying "why"	Explanatory
Why do such waste and deficiencies arise, and what causes them?	Why	Explanatory
How to innovate the process of supplying joinery products to construction?	How	Exploratory

In Table 2 the nature of the research questions is presented, and it can be seen that the research questions, rather than being explanatory, have a how and why nature. Furthermore, the control over events in the studied "real world" cases (Robson,

2002) is considered to be low, and the focus is on the current situation of supplying joinery products to construction rather than on past events. These are circumstances that justify a case study approach (Yin, 2003).

2.2 Researcher background

In qualitative studies, the researcher is an instrument for collecting and analysing data in their natural settings (Miles & Huberman, 1994; Denzin & Lincoln, 2000). It is not possible to collect and analyse data in research without an awareness of the possible biases due to the researcher's background and subjectivity (Meredith, 1998). However, the researcher's critical awareness of his/her presence in the studied situation, the choice of data collection techniques, and personal influence on analysis and conclusions are means to reduce the possible biases (Merriam, 1994). In this thesis, quantitative but mainly qualitative methods have been used; therefore, the researcher's background is presented to give the reader an opportunity to validate the possible bias in the researcher's analysis and conclusions.

The researcher has a BSc in Electronics and Computer Science with experience in designing quality processes and management at the Optronic group, software development and project management at Tieto and Ericsson, and ICT strategies in his own consultancy business. The researcher has worked in organizations with different levels of management quality and attitudes to the work process. Throughout this period, reflections on the process were always made with the purpose of finding ways to improve quality and/or efficiency.

The researcher subsequently achieved an MSc in Wood Technology and gained experience in developing processes and products in modified wood. During this period, local, national, and international contacts were made in the wood manufacturing industry (e.g., Martinsons, Snidex, Setra, Ute-trä), with architects (e.g., Nilsson and Sahlin architects, White architects), with suppliers of technology to the wood processing industry (e.g., Valutec, Kebony, Transfurans), and with research organizations (e.g., Luleå University of Technology, SP Trä). Thus the researcher has experience in both industry and research and has been meeting and interacting with people of different background and working at different levels, from management to blue collar workers, and this is seen as a valuable asset in the case studies during the collection of qualitative data.

During the research, the researcher has been involved with the European Union Objective Two project of Flexible Wood Manufacturing with the aim of developing processes and technology in the secondary wood processing industry, where the efficiency in supplying joinery products to construction has been the focus for the researcher. Industry representatives have been following the research project through a steering committee and allowing research in their businesses. Their involvement in this research project has enabled the researcher to enhance the general understanding of the studied phenomenon from various perspectives as well as informal communication with representatives of the studied organizations, resulting in a wider understanding of the studied context.

2.3 Research design and process

Research design is defined as an action plan that describes, in a logical sequence, how to connect empirical data to the study's initial research questions (Yin, 2003). A unit of analysis is defined as a component related to the fundamental description of the case and will have an impact on the research design (Yin, 2003).

The research design in this study involved conducting three case studies following two supplier projects of a major Swedish supplier of joinery products, with the unit of analysis being defined as: "*the process of supplying joinery products to construction*" as a general theme. The first case study focused on the interaction in the supply chain and on the construction process in terms of the client, the architect, the engineer, and the construction contractor. Thus, in the first case study the unit of analysis was defined as: "*the interaction between actors in the supplying of joinery products to construction*". In the second study the unit of analysis was: "*what waste (according to the Lean definition) is surfacing in the supplying of joinery products*". Finally, in the third case, the focus was on the process of verifying as-built spatial information from the environment, thus the unit of analysis was: "*the process of verifying as-built spatial information at the construction site"*. With these units of analysis, the current process of supplying joinery products to construction has been investigated and findings have been used to define deviations from Lean principles and other problem areas in information validation.

This type of research design is seen as 'abductive'; after gaining knowledge from the first case study, the researcher learned new facts that were then considered from a lean production and lean construction theoretical standpoint. Therefore, the researcher could expand the theoretical knowledge and understanding in the empirical context along with the progress of the study.

Yin (2003) emphasises the importance of thoroughly describing all research procedures to enable a reader to form his/her own opinion about the reliability and validity of the results. The research design has elements of flexible design

(Robson, 2002), as the design has evolved as the research proceeds. The abductive approach and flexible design were important to adapt the research to the investigation of a type of industry with very limited representation in the research society and to the limitations in the researcher's knowledge of applicable theories.

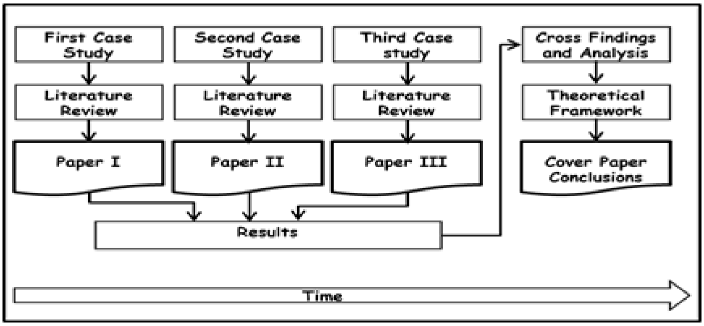

Figure 3: Research process

In Figure 3 a schematic representation of the research process in this thesis is presented. The research consists of three empirical studies, which have resulted in three papers. From the three appended papers, selected results have been extracted and a cross paper analysis using the model of analysis is made in order to answer the research questions included in the cover paper. Below is a brief description of the rationale for the three empirical studies performed within this research project and the associated appended papers.

2.3.1 Paper I

The research in Paper I was initially of a quantitative nature, trying to validate 3-D measuring technology that was considered important in developing the process of supplying joinery products to construction. A "real world" case study (Robson, 2002) was developed in cooperation with a Swedish joinery products supplier working on an engineer-to order basis who had an upcoming supply project that was considered challenging to verify spatially with their current technology. The researcher contributed to the project by using 3-D measuring technology–the coordinate measuring machine Proliner 8[1]–to verify the spatial environment (a stairwell in a new twelve storey building) and supplying a 3-D CAD model based on the measurements. This was performed in two steps. First, a limited section was

[1]http://www.prodim.eu/subpagina/1/1288606642111/actief/1288609493111/Proliner%20®%208%20Series (Retrieved on 2012-02-29)

measured and a prototype joinery product was produced according to the measurement information and assembled on the construction site. Secondly, the whole object was measured and selected parts were assembled in a 3-D CAD model and provided to the joinery products supplier for use in the production pre-processing together with all measurement data. Thirdly, the case was evaluated in a qualitative fashion in order to create an understanding of the process and the effects of including the 3-D measurement data in the process.

In the qualitative part of the case study, it was evaluated from a systems perspective and a case analysis was carried out using a hermeneutic qualitative approach with the purpose of enhancing the knowledge of the interaction between different actors and the practices that apply.

Data were collected through direct observations, semi-structured interviews, and project documents. Observations were made as the supplier project progressed, as the researcher made contacts with various people involved in the supplier project. Mainly the preparatory actions on the construction site before production pre-processing and manufacturing together with assembly work on the construction site after the manufacturing of the joinery were directly observed. Observations of the production pre-processing and manufacturing were further reconstructed afterwards during a visit to the factory and during interviews.

The use of semi-structured interviews meant that an interview guide was developed prior to the interviews (APPENDIX 1), but questions outside the guide were also asked during the interviews according to what was important to the respondent and what the researcher found valuable for improving understanding. According to Bell (2006), structured interviews strictly follow a guide, while semi-structured interviews are less formal–they follow a guide but the interviewer or respondent can lead the conversation to an area of interest. The purpose of the interviews was to enhance the understanding of the process and the interactions.

The structured questionnaire was divided into six main areas, each of which had about three to seven lead questions, open in character and with possible sub questions or new questions arising during the conversation. The interview questionnaire is presented in APPENDIX 1. The main areas of interest in the interview questionnaire are as follows:

- A description of the current process
- Conditions for the respondent's work

- Interaction along the value chain of the construction project
- Information, communication, accumulation, and exchange across disciplines
- Prerequisites and the need for measuring equipment
- Pros and cons of the project as experienced by the respondent

The respondents for the interviews were practitioners in the construction project studied, and to which the joinery products where supplied, and actors in the value stream of supplying those products. The respondents were chosen based on their specific knowledge and position to provide relevant information about the process. The respondents included: 1) the client procuring the construction project, the architects of the project, 2) the site manager of the construction contractor, 3) the construction engineer, 4) the client-contracted construction coordinator, 5) the construction contractor, procurer of suppliers, 6) the construction contractor surveyor, 7) the construction contractor staff realising the environment adjacent to the joinery products, 8) the sales manager of the joinery products supplier's sales organization, 9) the sales calculator of the joinery products supplier's sales organization, 10) the assembly procurer of the joinery products supplier's sales organization, 11) the production manager of the joinery products supplier, 12) the production pre-processing staff of the joinery products supplier, 13) the manager of the assembly contractor, and 14) the staff of the assembly contractor performing the assembly. In all, interviews with 18 persons were performed, recorded, transcribed, and supported with detailed notes.

Further project documents, such as contracts, drawings, organization charts, and cost estimates, were used to verify and to understand more about the interactions and the process.

The data collection needed to be documented for analysis of the empirical material. The observations were documented in pictures and notes; from the interviews both notes and recordings were taken, transcribed, and filed on a server, and the case project documents were copied and filed on a server and in binders.

Each interview, document, and observation produced data, but it is the combined results of the interviews, documents, and observations that generate the significant contribution to the analysis.

2.3.2 Paper II

The study in the second paper focuses on gaining a detailed understanding of the practices and obstacles in supplying joinery products. Again, a "real world" case study (Robson, 2002) was developed in cooperation with a Swedish joinery products supplier working on an engineer-to order basis. The focus in this work is on the potential for efficiency innovation in the process of supplying joinery products to construction, and the study was carried out as qualitative case analyses using a system approach. The staff members are skilled in their particular fields, but the process is not well documented. This lack of documentation makes systematic analysis difficult. Therefore, the need for documentation of the process in action emerged.

The study covers the process from quotation through order, production pre-processing, and logistics to the final product assembly on the construction site. Here, special attention has been paid to the assembly on-site to reveal any problems surfacing here at the end of the value stream. It is assumed that the cause of many of the problems occurring at the end of the value stream can be found upstream in the supply chain and that what is revealed here can be related to what is found in the upstream studies. Due to the engineer-to-order nature of the project, the study goes downstream instead of upstream as in value stream mapping of line production flows (Rother & Shook, 2003).

Data were collected through 1) direct observations during production pre-processing and manufacturing in the production facilities, during surveying, and extensively during assembly, 2) semi-structured interviews, and 3) project documents.

Observing behaviour gives opportunities to make sense in a wider context and draw conclusions that individual subjects might have difficulty noticing (Merriam, 1994). Further observations provide an opportunity to complement information from interviews and are a valuable tool for revealing discrepancies between what respondents say they do and what they actually do (Robson, 2002). Therefore observations were conducted in order to better understand the various aspects of the process. Full-time observations were made on the construction site during surveying and assembly, while the observations on the production facilities were more of a "gemba walk" nature (Womack, 2011) where the researcher is the important instrument. The observations were documented through notes, photographs, and audio recordings. The depicted scenes gave an opportunity to reflect on specific situations in retrospect and to compare them with what was said in the interviews. The on-site observations also enabled gathering of information that the participants were unable or unwilling to fully disclose in interviews or through documentation.

Semi-structured interviews were performed with individuals engaged in different activities in the supplier project. An interview guide was developed prior to the interviews, but questions outside the guide were asked during the interviews in a semi-structured style (Bell, 2006). There were interviews and/or conversations with individuals from the sales department, production pre-processing, manufacturing, the forwarding agent, and assembly procuring and planning, the assembly contractor staff and management, the delivery receipt contractor, the construction contractor site manager, and architects involved in the construction project. The objective of the interviews was to enhance knowledge of how the process was perceived and how the organization was arranged. In addition, the interviews focused on how the supplier organization related to the surrounding actors.

Results from the interviews, observations, and documents were used to produce a model of the information flow and problems arising within the project. In the analysis, empirical material from both the second case and the first case described in Paper I were used, though with a weighting towards the material from the second case. The analysis was focused on defining different types of waste surfacing in the studied cases and possible areas of innovation. The information flow and knowledge exchange across organizational borders was of special interest. The causes of these problems were analysed and generalised using principles of Lean production and supply-chain management. To improve the productivity of joinery product companies, ways to innovate in the internal process through Lean principles, modelling of information, supply-chain planning, and coordination were explored.

2.3.3 Paper III

Paper III focuses on obtaining as-built spatial information from the environment in which the joinery products are to be placed and fitted. This is information the joinery products supplier needs before starting the production to verify the spatial information provided by the procurer. There are two areas studied: the current practices and obstacles for the joinery products supplier in surveying the adjacent environment of the products, and the use of available 3-D measuring technology that is more advanced than the technology currently used by the joinery products supplier studied in the "real world" case (Robson, 2002). The studied supplier project is the same as in Paper II, but here analysis of the current practices in the process is limited to obtaining the as-built information. Therefore, the same methods apply as those described for Paper II when considering the current practices and obstacles for the joinery products supplier.

The use of more advanced 3-D measuring technologies was applied to the same physical objects and at the same time (day) as the surveying performed by the joinery products supplier. The three different technologies were studied qualitatively and to some extent quantitatively and compared against current practice used by the joinery products supplier.

2.4 Validity and Reliability

Validity and reliability are criteria used in qualitative research to assess the quality of the research. In contrast to verification, which in general terms means "*doing things right*", validation is concerned with "*doing the right things*" (Lucko & Rojas, 2010).The four tests of 1) construct validity, 2) internal validity, 3) external validity, and 4) reliability are commonly used methods to establish the quality of empirical data in qualitative research and in case studies (Yin, 2003).

Construct validity refers to the extent to which a study investigates what it is claimed to investigate, and that correct operational measures are used to accurately observe the reality (Denzin & Lincoln, 2000; Yin, 2003). By establishing a chain of evidence, based on multiple sources of evidence, the researcher can enhance construct validity. Throughout the study, multiple sources of evidence have been used for data triangulation, and multiple researchers have participated to minimize the bias of a single researcher, thus enhancing internal validity.

Internal validity is related to the concept of causality and is preoccupied with the derivability of relations within data (Leedy & Ormrod, 2005). As the performed cases aim to be explanatory, this becomes applicable in this research, and the use of a research framework–comparing our own empirical findings to other research–and theory triangulation are thought to enhance the internal validation of this study.

External validity relates to the possibilities of making generalisations of the case study results. Here it should be noted that external validity concerns an analytical generalisation from empirical observations to theory rather than a population as in statistical generalisation when using a survey strategy for the research (Yin, 2003). As the cases are chosen due to the nature of being difficult to verify spatially for the joinery products supplier and thus adding uncertainty to the projects, they can be seen as extreme cases and are thus more likely to reveal more information (Flyvbjerg, 2006). This, together with the use of nested case studies, adds to the external validity despite the limited number of cases and organizations studied (Cook & Campbell, 1979; Yin, 2003).

Reliability requires consistency and repeatability and is achieved when a researcher can demonstrate that data collection can be repeated with the same result. Reliability aims to reduce errors and biases in a study (Yin, 2003). Yin points out that the emphasis is on doing the same case study over again, not on replicating the results of one case by doing a different case study, which would be difficult in this research due to the one-of-a-kind nature of construction, which is the research arena in this study. Continuous diaries of the research work are maintained, the empirical material is documented thoroughly through notes, voice recordings, and photographs, and during interviews an interview guide is used. All this is to enhance transparency and repeatability in order to strengthen the reliability.

3 Results & Discussion

In the following chapter, results from interviews, observations, photographs, voice recordings, and documents are discussed. Due to the vast amount of information, not all evidence material is presented here. This discussion is based on the results presented in appended papers. Parts of the material from interviews and observations can be found in those papers. In the following, the appended papers are summarized, the process of supplying joinery products to construction is described, and then experiences from the appended papers are cross analysed.

3.1 Paper overview

Paper I

In Paper I, the focus is on the interaction between the joinery products supplier and the construction process. There are four main waste generators identified: (1) information needs are not met; (2) competence is lacking; (3) there is a lack of activity in the gathering and mediation of information; (4) inventory of information documents breaks the flow of value-creating activities.

This study shows that interaction is hampered by poorly defined interfaces, lack of standardization, and lack of feedback on design and method information that are waiting for further processing and as a result the actors in the value stream are distanced from each other. One solution could be to agree on the supplier interfaces with the contractor organization, and also with the architect and the client. This calls for different behaviour towards the suppliers in construction, and more integration of contractors and suppliers is needed to progress towards a model in which all the parties strive to supply customer value at the lowest possible total cost.

The case findings show that supply-chain management and information management are the two main areas with potential for improvements, causing numerous knowledge disconnection effects for the joinery products supplier in construction.

Improving the standardization of the interfaces between the actors in the construction value stream, starting with the nearest downstream actor in the value stream, is suggested. This would lead to an improved information flow in the value stream.

Paper II

Paper II focuses more on the supplier process itself, with special attention given to problems surfacing late in the process. In Paper II, two main areas are identified as being the cause of much of the waste surfacing. These are:

- Procurement model
- Information standardization and communication

A procurement model based on a more long-term relation than project level is desirable. Over-processing in the business transaction could be avoided as an advantage of more concurrent and interactive work between those who create value, in these cases, the architect, and pre-processing, production, and assembly personnel. This would provide more efficient knowledge accumulation through the value stream, since information would be shared and mutually developed.

Many of the information communication problems observed originate from the suppliers' own processes and then surface during assembly. Assembly inefficiency problems are within the power of the joinery product suppliers to address. Three major contributors to assembly inefficiency were found in the studied cases:

- Inadequate planning and coordination
- Absence or inadequacy of assembly information
- Spatial uncertainties

All three of these relate to exchange, sharing, and modelling of information. The case examples show severe limitations in planning and coordination, which is proven to lead to work flow uncertainty and thus loss of work efficiency (Tommelein, Riley, & Howell, 1999).

Absence or inadequacy of assembly information disturbs the flow and process efficiency. It would be possible to achieve increased efficiency in the assembly knowledge build-up through efforts in the 3-D modelling of the joinery products. Making the information easily understandable and usable in the assembly situation is an important issue in improving assembly performance.

Despite the efforts of joinery products suppliers to verify spatial as-built information, their methods cannot eliminate the spatial uncertainties. These uncertainties decrease efficiency in both production and assembly, and this hampers the predictability of the process.

Paper III

In Paper III, the process of retrieving spatial as-built information when supplying joinery products to construction is examined. The focus is on how the evaluated technology performs in the process of supplying joinery products to construction.

In the case of the joinery products supplier, the currently used methods of retrieving the as-built spatial information have been mapped. In parallel, the use of 3-D measuring technologies has been evaluated in the same environment as the real case of the joinery products supplier.

Three types of 3-D measuring technologies have been evaluated: a Proliner 8 coordinate measuring machine (CMM), a photogrammetry setup with a Nikon D50 camera and Photosynth software, and a laser scanning with the Leica Scan Station C10.

This paper builds on the experiences of currently used methods in supplying joinery products and their problems as outlined in Paper I and Paper II, and on experiments using the 3-D measuring technologies in attempting to improve the spatial certainty. As the earlier papers have shown, the spatial uncertainties affect the efficiency of production pre-processing, production, and assembly work. Thus the elimination of spatial uncertainties can yield predictability of those steps in the process, especially in the on-site assembly work, and increase the process efficiency. Furthermore, a digitized model of the as-built reality can be used to adapt the CAD models of the joinery products and to control numerically controlled manufacturing equipment, which can produce accurate products efficiently. The higher degree of modelling would provide a solution for more of the detailed work that is currently performed at assembly and allow for a higher degree of prefabrication of the joinery products.

The three 3-D measuring techniques tested in this work give somewhat different conditions on how to use the information and on the limitations in precision. All three techniques can enhance the process of acquiring as-built information compared to currently used methods in terms of the amount of information and 3-D relations. Still, all three methods simplify the data in the transformation to a 3-D model, which impacts the reliability of the virtual reality created by the measurements.

In the work presented, it is shown that the traditional methods of measuring as-built dimensions differ quite considerably from the tested 3-D measuring techniques. Spatial deviations of walls and floors are not considered at all with the currently used manual methods. Of the tested equipment, laser scanning yielded the greatest amount of spatial information and probably the most accurate, but still there were limitations in the models of the as-built reality that raise doubts about the performance.

In the manufacturing of the joinery products, it is possible to achieve tolerances of less than 1 mm. To retrieve a 3-D spatial as-built virtual model with accuracy in all aspects comparable with those tolerances still seems difficult using the 3-D spatial measuring technology tested in this paper. Not all problems related to the spatial uncertainties can be eliminated, and whether this is good enough to adopt some of the tested technologies needs to be further investigated. Therefore future work is needed in the area of 3-D spatial scanning and modelling of as-built information for supplying joinery products to construction, as well as on the effect of the process on the current measuring performance.

3.2 The process of supplying joinery products

The process of supplying joinery products to construction as seen in the studied cases can be described by the value stream map in Figure 4. The supplied products are engineer-to-order products. This means that the first stage in the process is the sales effort in advertising and making quotes. Then, when orders are received, production pre-processing refines the information in the order into a product definition and work orders. In parallel, assembly work is planned and procured. After manufacturing of the product components, they are transported to the construction site and assembled by an external contractor. In the following sections the process is described in more detail together with observations from the two cases of problems that are generating waste.

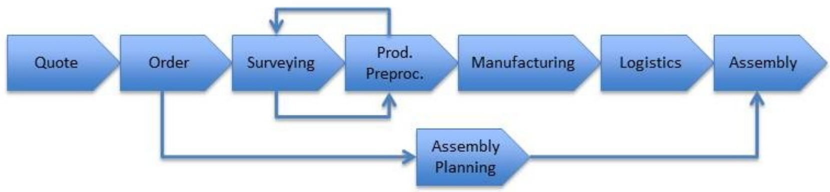

Figure 4: Value stream of the studied cases

Sales process – quote to order

The sales process targets the traditional construction industry. Generally a *design-bid-build project delivery* (Forbes & Ahmed, 2011) is used, where the construction contractor sends out quotation requests to joinery products suppliers for products that are often prescribed by an architect who visualises the client needs. The quotation requests are processed by a sales department that estimates cost and market value in making the quote. The construction contractor sends out quotation requests to possible suppliers in two cases: (1) when the contractor is making calculations for a possible project and is supposed to produce a quote for a client in the early stages of the product determination stage, and (2) when the contractor has received a project from the client, that is, in the late stages of the product determination. The quotation requests are often guided by quite detailed and complex regulations. Apart from the regulations, there are often varying degrees of detailed definitions and specific demands that are open to interpretation by both sides, and the contract form is *fixed lump-sum price* (Forbes & Ahmed, 2011). In both cases, the quotation request is sent to several competing suppliers with no compensation for the work involved.

Observed problems

In the studied cases, procurement is done on a project level and takes much calendar time compared to the time taken for realising the product. For example, in one of the two cases, 81% of the calendar time was for the procurement while, upon receipt of the order, the remaining 19% was used for engineering, producing, transporting, and assembling the product. In the second case, this relation was 60/40. Thus more calendar time is used for the procurement than the actual realisation of the ETO product. Related to this model for procurement, much calendar time passes between the architect's product definition and the joinery products supplier's product definition, which hampers the knowledge exchange between those specifying the value of the product and affects the extent and quality of the design work. This affects the level of prefabrication, since more of the product solution is left to be performed in assembly with craftsmanship methods.

Production – surveying to logistics

When the sales department receives the order, accumulated information from the sales process is transferred to the production pre-processing section. Now production pre-processing starts the work of defining a product from the given information, deciding production methods, scheduling the production, and ensuring that spatial as-built information is acquired. Since joinery production requires tighter tolerances than construction in general, provided drawings are not sufficient. There is a need to verify the spatial as-built information by measuring the environment for the products and comparing it to the supplied drawings, and to adjust the product solution to prevailing circumstances. This measuring is performed on the construction site, generally by the joinery products supplier. The measurements involve a risk if they prove to be insufficient, inaccurate, or more time-consuming than planned for in the quote. Furthermore, the making of measurements on-site requires coordination with the construction project. The time required to perform the measurements in a project varies from a few hours up to hundreds of hours in some cases, and the time needed is difficult to estimate accurately from the prescribing documents when making the quote.

Manufacturing of the joinery products is performed using information produced in the pre-processing. This information is communicated mainly by 2-D drawings and a manufacturing bill. A production plan is used to show the manufacturing time requirements. The main support for this work is CAD software and the companies' own routines developed for creating manufacturing bills and production plans for the production staff.

Before transportation, groups of product components are put together in parcels. The transport of components from the factory to the construction site is performed by a forwarding agent.

Observed problems

Currently, mainly manual methods are used to acquire the necessary spatial information. These measurements are done on a 2-D basis and with a few measuring positions; therefore, they do not deliver all available and required spatial information to eliminate spatial uncertainties.

The production units studied are small companies with fewer than 20 employees and with limited resources for process development. Much of the defining work is performed by a single person in production pre-processing in these companies and is a role with periods of high workload. There are few routines for quality control of the pre-processing, and logical errors in design/pre-processing have been seen to pass down the value stream and are not revealed until the assembly. The product solutions are sometimes under-processed, which generates more work in assembly and hampers the predictability of the assembly work.

The labelling of the manufactured components in the parcels is not always satisfactory and, together with the absence of assembly instructions, this hampers the efficiency of understanding the assembly of the product. Furthermore, there is limited control of the transport service from the production unit to the construction site in terms of delivery time and allocation of resources for unloading.

Assembly planning – order to assembly

The main tasks of assembly planning are to contract assembly contractors and to coordinate these resources with the tact time of the production and the demands of the procurer. This function also participates in the quotation process, where the cost for the assembly work is estimated. The studied supplier works on national and, to some extent, international markets, hence the projects are geographically spread. The strategy applied is to contract assembly contractors close to the construction site. During the assembly, this function follows the on-going assembly projects to support and to deal with potential problems.

Observed problems

The level of detail in the assembly planning is low and no tact time is specified, which makes it difficult to know whether the pace of the assembly progress is such that it will succeed within the contracted time.

Assembly on-site

The final assembly of the joinery products is performed on the construction site by local assembly contractors. To perform this work, an understanding of the products that are to be assembled is needed. The support for developing this understanding is the supplied information. The main information carriers are 2-D drawings from the architect and occasionally some sketches from the pre-processing. Assembly instructions or exploded views are generally not supplied to the assembly contractor.

At the construction site, the assembly contractor receives deliveries from the production unit. When the components arrive at the site, the assembly contractor generally needs to communicate with the production pre-processing personnel in order to develop an understanding of how to assemble the product.

On the construction site, the assembly contractor often needs to coordinate their work with other contractors on-site, and this is usually done ad-hoc.

Observed problems

The locally contracted assembly contractors are not necessarily familiar with the ETO products that are to be assembled, and instead of assuring good information support for these contractors the ad-hoc problem-solving skill of the contractor is rewarded. The development of a detailed understanding of the assembly work usually starts when the components arrive to the construction site, and this requires some time to develop. With easily understood, detailed information, this understanding could start before the arrival of the joinery products components on the construction site. As the components are not always labelled and drawings or sketches showing how the components relate to each other are not always provided, the understanding of how to perform the assembly is hampered.

Arrivals of deliveries are not coordinated with the assembly needs but rather with the time of manufacturing, thus they are pushed to the construction site, and inventory buffers at the construction site are needed. The logistics from manufacturing to assembly are not controlled in the studied supply chain. Imprecise timing of parcel arrival on-site and parcels in sizes that do not always fit the in-transport routes at the construction site make the receipt of deliveries time consuming and unpredictable in terms of resource utilization. Thus the design, timing, and information provided with the parcels of joinery products components have an impact on the efficiency of the assembly work.

In production pre-processing, an idea of how to perform the assembly is developed, sometimes in cooperation with the assembly contractor. Still, much of the assembly method needs to be developed ad-hoc on the construction site. The need for direct communication with the pre-processing often disturbs the assembly work due to accessibility difficulties.

Detailed planning of what to do and when is often limited; mainly it is the start and the desired stop dates that are known, thus coordination with other contractors is hampered. These conditions contribute to a rather low predictability of the assembly work.

3.3 Cross analysis of papers

In the following sections the appended papers are analysed against principles of Lean and information management. Important areas hampering process efficiency are identified, and ideas for innovation in improving process efficiency are presented. In APPENDIX 1 the appended papers are analysed against the areas identified as needing innovation.

3.3.1 Waste – non value adding

The study shows that time and effort are put into the process of supplying joinery products to construction that do not add value.

The concept of value in Lean is a well-explored topic in research literature. In short, focus should be on maximizing the value in the eyes of the end user; however, in supplying joinery products to construction the supplier is not in direct contact with the end user. The procurer of the joinery products supplier is usually the construction contractor and therefore affects the definition of the value. Furthermore, the architect, who often prescribes a general design of the product which should reflect what the client values, also has an agenda regarding what adds value to the joinery product. Here, the discussion on maximization of the value for stakeholders in this value-chain is not considered. Instead, the concept of waste is used, and the focus is on minimizing the waste. Thus, in this thesis the focus is on the efficiency rather than the effectiveness of the process. Effectiveness concerns the doing of the right things, the management of the project, while the efficiency is concerned with doing things right, the logistics in the work of the project, the work flow (Drucker, 2007; Fearne & Fowler, 2006). Thus, an effective process ensures that the intended result is achieved and is run efficiently if no waste in time and effort is generated. This can also be related to Lean principles and the waste definition used in Lean literature (Liker, 2004; Womack & Jones, 2003).

Based on the definition of waste according to the seven wastes of Lean (Womack & Jones, 2003), problems in this process have been identified. In Paper II this is highlighted using the TIMWOUD acronym, which is a variant of the TIMWOOD acronym that is used for describing the wastes of *Transport, Inventory, Motion, Waiting, Over-processing, Over-production*, and *Defects*.

In Paper II, the potential for efficiency improvement by eliminating waste from the process is illustrated in Figure 5. Here the importance of identifying the root cause of the identified waste at a cross-organizational level is highlighted. Lean principles are suggested as guidance in this work.

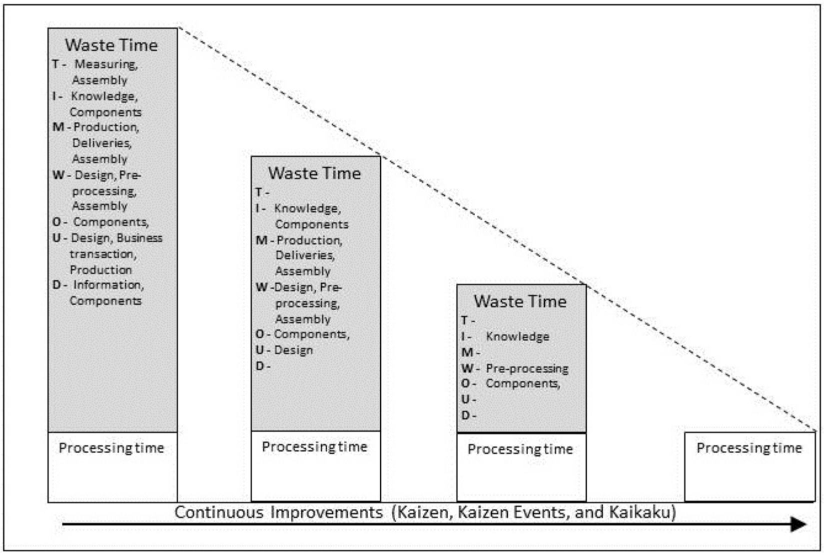

Figure 5: Waste elimination as a means of improving process efficiency (after Koskela, 1992)

Experiences from both Paper I and Paper II are examined against Liker's (2004) 14 management principles, and some important violations of these principles can be found. This can be summarized in four areas: 1) Long-term philosophy–the contractual relations work on a project level, therefore there is limited long-term development over the supply chain; 2) The right process will produce the right results–minor resources are used for developing the process, and each node in the supply chain limits the cooperative development of the overall process; 3) Add value to your organization by developing your people and partners–the supplier works in a network for the sales but does not use the full potential of the network for developing mutual processes and finding the best practice among them; 4) Continuously solving root problems drives organizational learning–currently, problems are solved as they emerge. With this culture, problems are not detected and reported as problems, and thus the root cause is not analysed. Therefore limited organizational and inter-organizational learning takes place through the value stream, and problems reoccur repeatedly.

3.3.2 Less business transaction and more value adding

In Paper I, the time relation between the business transaction and the time when value is added to the product is highlighted. In Figure 6, the timeline of the construction project and the joinery products supply project for the case study in Paper I is presented. In this case, 94 weeks elapse from the preliminary quote until the order is received. Much of this time, for processed work such as the quote and prescribing documents, is spent waiting, thus no value is added. During this time span, the major focus and efforts are invested in the business transaction. Then in 19 weeks, the product is to be engineered, produced, and assembled on the construction site.

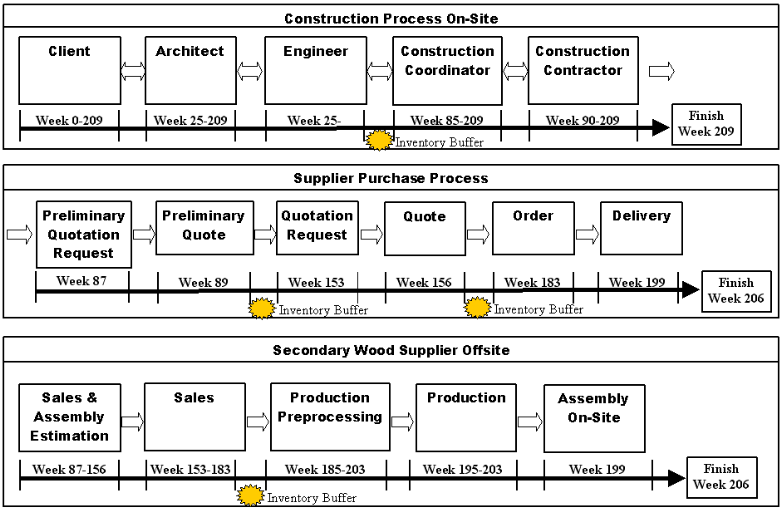

Figure 6: Timeline of construction and supplier process in Paper I

This time delay limits the interaction between the supplier and the architect whose prescriptions are to be defined into a product solution. This can affect the quality of the solution in terms of customer value, since the architect's work is to visualise the customer need, a vision that the joinery products supplier is to realise into a product.

This is also seen in Paper II, where the necessity for procurement on project level is questioned, and it seen to obviate major gains in applying concurrent engineering methods to the value stream. Here it is argued that in supplying joinery products, production pre-processing is central; it is where the architectural ideas are formulated into products and where ideas about assembly methods are created. Long-term procurement relations with less focus on the business transaction would enhance integration and information exchange between the architect, production pre-processing, and assembly in the product determination, as observed by Bystedt (2007).

An effect of this skewed distribution of activities during the project time is under-processing of the product definition and of the planning and coordination. Therefore, problems pass down the value stream and have to be solved late in the supply process. This makes the total process more unpredictable and less efficient.

3.3.3 Needs for information management

An important measure to eliminate waste lies in the management of information. In the cases studied in the appended papers, information is a central part of the total process, as more and more information is accumulated before the final realisation of the product. As the process evolves, knowledge is built up across organizational borders. To enhance this knowledge build-up through the value stream, information needs to be accurate, achievable, accessible, and understandable for all stakeholders.

In Paper I, the information exchange and supplier interaction is illustrated as in Figure 7. This project involved the supply of an advanced joinery product to a new office building. The client ran the project using a web-based information platform for the actors involved in the project. Though mainly on-site actors where connected to this information platform, the joinery products supplier was not aware of, nor connected to, this platform. The connection of the joinery products supplier to the information platform was simply overlooked by the client, who had no intention of restricting information access.

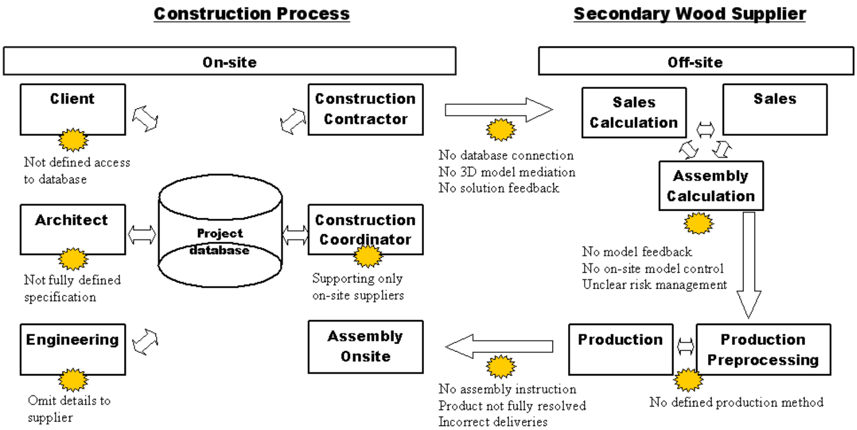

Figure 7: Process interaction and information exchange

As a result of this disconnection from information, the joinery products supplier wasn't aware of the 3-D model already performed by the architects and made one of their own, which contained errors. This resulted in erroneous product components being manufactured and transported to the construction site, and thus affected the assembly work as well. In this case the information wasn't accessible for the supplier.

Furthermore, in Paper I the situation of making a business transaction based on incomplete information is discussed. The information from the prescribing part is seldom fully defined; details are deliberately left out for the supplier to solve. When pricing the joinery product, the estimation is done based on supplied information, and since this work is not chargeable, the resolution of the estimation in the quotes tends to be limited, thus projects involve a risk in profitability. Then, when the order is received and production pre-processing personnel are engineering the product, interaction with the prescribing part would be appropriate, but this seems not to be the normal routine since this is believed to affect the lead time. Thus, the understanding of the supplied information is not verified and information exchange with adjacent processes is limited.

In Paper II, the focus is more on the supply chain of the joinery products supplier. Here it is found that deficiencies in the supplier's information management are a major contributor to the identified inefficiencies. Many of the problems in the supply chain surface late in the process, when assembling the product on the construction site. The following are found to be the major contributors to assembly inefficiency:

- Inadequate planning and coordination
- Absence or inadequacy of assembly information
- Spatial uncertainties

All three relate to sharing, exchange, and modelling of information. From a Lean perspective, process flow is central. Tact and just-in-time (JIT) concepts are essential in establishing flow, which requires planning and coordination when working in a cross-organizational manner. It is seen that the tact of the assembly work is not defined and the arrival of the components of the joinery products are not coordinated with the need for them in the assembly, thus the concept of just-in-time is not used and the components are stored at the construction site, which causes more transport of materials and motion for the workers. Furthermore, the risk of damage of components increases when they are exposed to the environment on the constructions site.

Much of the information that needs to be managed can be modelled, making it more visual and easier to survey. Adoption of the principles of the Last Planner system (Ballard, 2000), integrated project delivery (American Institute of Architects, 2007; Forbes & Ahmed, 2011), and Line of Balance and 4D/nD information modelling (Björnfot & Jongeling, 2007) seem to be potential innovations for the problems in the area of planning and coordination. Further efforts in 3-D modelling are also suggested in approaching the problem of assembly information.

3.3.4 Approaching concurrent engineering

Concurrent engineering, a method where product and production development are performed in parallel, has been found to yield shorter lead times and higher quality products compared to sequential engineering (Sohlenius, 1992). In construction, fragmentation is known to be substantial and concurrent engineering is seen as a tool to decrease that fragmentation (Love, Gunasekaran, & Li, 1998). Karlsson, Lakka, Sulankivi, Hanna, & Thompson (2008) studied construction cases in Europe and the US where concurrent engineering methods were used and found substantial time savings. The study also showed benefits in information exchange, communication of information and documents, and quality.

What is seen both in Paper I and Paper II is that increased integration between value-adding actors needed. In Paper II, the current process versus a process adopting principles of concurrent engineering is illustrated (Figure 8). Here it is suggested that the next downstream process can add directly to the accumulated knowledge. Ideally the process should be more concurrent and interactive, and information should be communicated efficiently through the value stream without any knowledge drop occurring in each downstream handover.

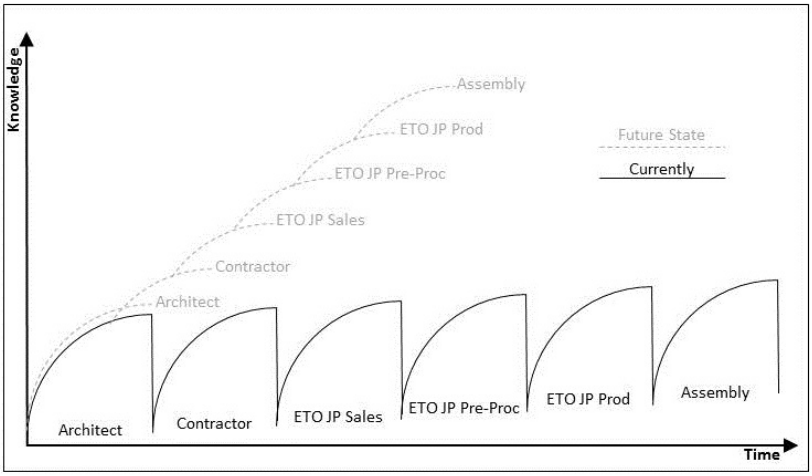

Figure 8: Potential of concurrent engineering approach

In the studied cases, production pre-processing is central; it is where the architectural ideas are formulated into product definitions and where ideas about assembly methods are created. The adjacent steps in the value stream need to interact and exchange information in a way that fosters mutual understanding of how decisions affect the process and the product. For example, the supplier product competence can be useful in the architectural determination that can enhance product quality and process efficiency.

In Paper I, it is pointed out that prescribers, such as architects and engineers in construction, deliberately leave out details in the suggested product for the supplier to solve, based on the assumption that the supplier is more of an expert at the prescribing part. However, the supplier thinks that they supply a product according to the prescribing documents. This gap in information and perception of reality calls for a routine where the supplier and prescribing party meet and exchange knowledge and together identify a product solution. Such direct communication between supplier and prescribing architect has not been seen in the cases of Paper I and Paper II.

To avail of the full potential of concurrent engineering principles, the supplier must be able to interact with the prescribers when they are performing the prescribing. This would require new forms of contractual relations.

The same procedure is suggested for the supplier and the assembly contractor, who can contribute to the method of assembly as well as increasing the knowledge of the project when starting assembly, which would be beneficial for the efficiency of the assembly.

3.3.5 Planning and coordination

In the cases studied, much attention is given to the business transaction and the design information. Planning, coordination, and assembly information is given little attention. To apply Lean principles in construction, the predictability of processes needs to increase, as shown in Howell (1999). When supplying joinery products to construction, planning and coordination are needed at several levels.

In Paper I, it is shown that in the quote, a specific production method is planned for in terms of time and resource allocation. However, when performing the work it was found that the planned production method wasn't feasible and more resources than planned for were needed in the production process. Thus the planning in the quotation work was insufficient and added uncertainty to the project. Here, uncertainty means the difference between the information needed to perform the supplying and the information already possessed (Galbraith, 1973). To reduce uncertainty, information needs to be acquired as the project progresses (Winch, 2003). Thus work that might not be considered in the quote needs to be performed to reduce uncertainty.

In Paper II, a number of problems surfacing during the assembly are related to deficiencies in planning and coordination. It is found that the tact for the assembly mainly works at a start and stop level. The exact details and available time for each moment are usually not known, thus there are uncertainties in this process that decrease the predictability of the work to be planned. Furthermore, it is seen that during the assembly, coordination is needed with other contractors on-site and this coordination is left to the assembly contractor to manage as the need arises. This adds motions and waiting time to the process and thus affects the efficiency of the assembly work. Furthermore, it is noticed that the management of other contractors during the assembly causes a change of the work at hand while waiting for another contractor to perform work needed before continuing the assembly at hand, which further decreases the predictability of the work due to insufficient planning and coordination.

It is also shown that the process of transporting the components of the joinery products from the production plant to the assembly site could benefit from increased planning and coordination. For example, the parcel arrival order, parcel size, and time of arrival show deficiencies in the planning and coordination between the assembly work and the production process.

In Paper III, it is shown that performing on-site spatial measuring requires coordination between the joinery products supplier and the construction contractor. The joinery products supplier usually makes spatial measurements to verify the given spatial information before production, and this need to be coordinated with the construction contractor. It happens that the adjacent surrounding for the joinery product is not produced when the supplier needs to perform this work before production. Therefore the best solution is to plan and coordinate the construction work to avoid this situation.

From what is shown above and in the appended papers, an increased level of planning and coordination is an important measure in striving for enhanced efficiency in supplying joinery products. For this to happen, the use of tools that enhance understanding of the process and increased visualisation, e.g., using line of balance and 4D modelling, could be investigated. To decrease the time for assembly on-site, an increased level of planning and coordination is suggested. To be able to achieve this, more time and resources are needed in the production pre-processing and assembly planning.

3.3.6 Need for as-built information

It is found that spatial uncertainties are a major contributor to inefficiencies in supplying joinery products to construction. There is a need for the joinery products supplier to verify the spatial as-built information by measuring the environment for the products and to compare it to the supplied drawings and adjust the product solution to prevailing circumstances. The drawings provided are generally not sufficient, since in construction the as-built production does not always reflect the prescribing documents, especially not with the level of tolerance used in the production of joinery products

In Paper I, the supply of a product that physically ranges through a twelve storey building is being examined. Here the product complexity is discussed, as well as the challenge in acquiring the as-built spatial information with traditional manual measuring methods. Not included in the paper was the work of measuring the adjacent environment for this product with a coordinate measuring machine in parallel to the manual measuring that was performed by the supplier (Figure 9).

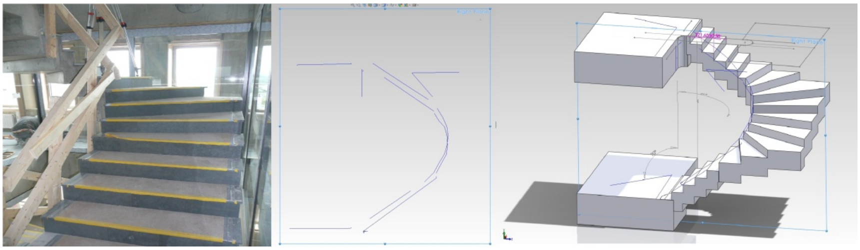

Figure 9: CMM measuring of stairwell with Proliner and the resulting 3-D CAD model

Aided by the test measuring with the coordinate measuring machine, a prototype component was manufactured and assembled on the construction site. This was considered sufficient testing, and production pre-processing continued with modelling of the product and the most adjacent environment. The work with the coordinate measuring machine continued in parallel. Still, there were problems with the trustworthiness of these measurements and with the competence of putting the measurements together in to a 3-D assembly for all twelve storeys. The manual measurement had indicated that the as-built information correlated rather well with the prescribing documents, and therefore the product was designed according to architectural drawings. Any problems caused by remaining spatial uncertainties where left to be solved when assembling the product. Thus, the tested methods couldn't eliminate all spatial uncertainties.

In Paper II and Paper III, the currently used methods for acquiring as-built spatial information prior to production are examined. In Paper II, the focus is on the overall supply process and on what hampers the efficiency of this process. Here the effects of the spatial uncertainties are identified. Then in Paper III, the focus is more on the measuring process and the use of currently available technology in attempting to improve the methods currently used by the joinery products supplier.

Traditionally, measurements are done on a 2-D basis and thus do not deliver all available spatial information. The measurements involve a risk if they prove to be insufficient, inaccurate, or more time-consuming than planned for in the quote. Furthermore, the making of measurements on-site requires coordination with the construction project. The time required to perform the measurements in a project varies from a few hours up to hundreds of hours in some cases, and the time needed is difficult to estimate accurately from the prescribing documents when making the quote.

In the studied organization, about 1700–2000 hours are believed to be used annually for performing spatial as-built measuring before production, which would correspond to a full-time employee specialising in performing this work, a role that currently is not present. However, the actual cost in the overall process that the spatial uncertainty of the as-built information contributes to is unknown. The spatial uncertainty is found to be one of the main contributors to the generation of waste in the process of supplying joinery products to construction. This waste is evident in production pre-processing when the product is engineered, in production, in the transport of components, when receipting the components on the construction site, and during the assembly. Thus the overall efficiency is highly affected by the problems of eliminating spatial uncertainties from this process.

In Paper III, the currently used methods for acquiring spatial as-built information are evaluated against currently available 3-D measuring technology. Three types of 3-D spatial measuring technologies have been tested—a Proliner 8 coordinate measuring machine (CMM), a photogrammetry setup with a Nikon D50 camera and Photosynth software, and a laser scanning with the Leica Scan Station C10.

What is seen is that the currently used methods in supplying joinery products to construction are rather manual. Tools such as tape measures, spirit levels, and laser distance meters are used to calibrate architectural drawings against the as-built reality in a 2-D sense rather than a true 3-D reproduction of the construction scene.

The investigated 3-D measuring technologies deliver measurement registrations in a coordinate space. This coordinate space is normally represented by three axes, X, Y, and Z. All measurement technologies have limitations in range and precision, and these can vary between the three axes.

The accuracy of one example of the Proliner 8 CMM has been investigated in more detail. This machine uses a stylus probe that is positioned against the object to be measured and a remote control to order the machine to register the position of the stylus probe (Figure 10). The stylus probe is connected to the machine through an extractable wire from a measurement arm that can be seen in Figure 10. The range of the wire is up to 7 m, and the measurement arm can be rotated horizontally 402 degrees and vertically 104 degrees; there are sensors that register the wire extraction and the horizontal and vertical positions of the measurement arm.

Figure 10: Measuring with the Proliner 8

The accuracy of these position sensors has been investigated regarding the variability when repeatedly measuring fixed positions along the range of the three sensors for the wire extraction and the horizontal and vertical positions of the measurement arm of the Proliner.

From Figure 11 it can be seen that the wire extraction sensor shows significant differences in precision depending on position, while the horizontal and vertical positions of the measurement arm of the Proliner do not significantly affect the precision. In Figure 11 A, the error of the wire extraction of the Proliner CMM with a 95% confidence interval is in the range 0.27–0.36 mm at 1 m range to 0.79–1.13 mm at 6.5 m range.

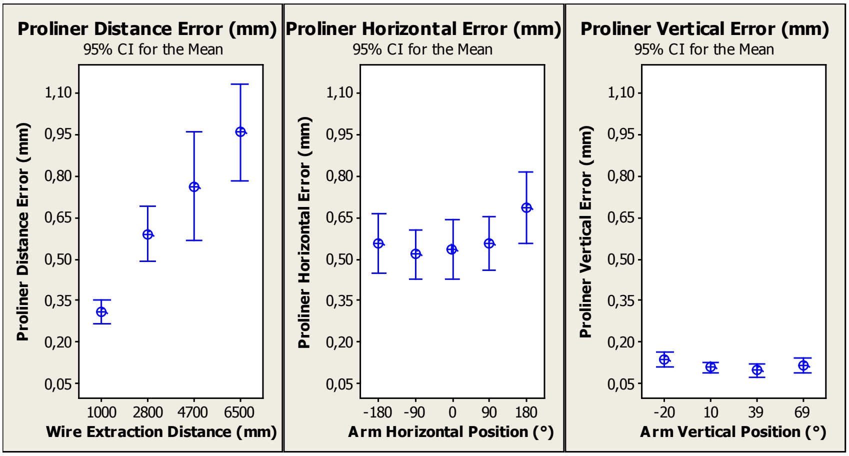

Figure 11: Size of the error along the range of the Proliner sensors for: A) Wire extraction position B) Arms horizontal position C) Arms vertical position

In the experiments performed for the graphs in Figure 11, the stylus probe registrations are done in a controlled environment. In real life, it is likely that some of the registered coordinates will have an error larger than that of the experimental values. Therefore a strategy is recommended where as many coordinates as possible are registered and average values of the registered coordinates are used. When using the Proliner at the construction scenes in the studied cases, the wire extraction is often in the upper range and therefore decreases the reliability of the measured data. Furthermore, it is likely that the distance from the sensor also affects the accuracy in laser scanning and photogrammetry technologies.

The three 3-D measuring technologies investigated differ in the number of coordinates used to depict the spatial information of the room. The Proliner CMM most resembles the manual methods currently used in supplying joinery products in that it makes rather few observations to describe something that holds much more information, while the other two can give a sufficient number of coordinates to give more information about details and more reliable information on the three-dimensionality of the measured object. These differences of the measurement information are illustrated by examples in Figure 12 and Figure 13.

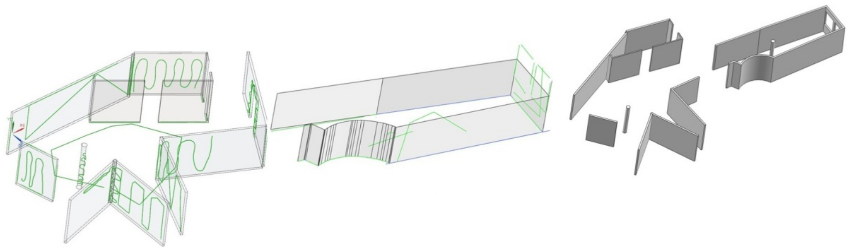

Figure 12: Measured data and model from Proliner measuring

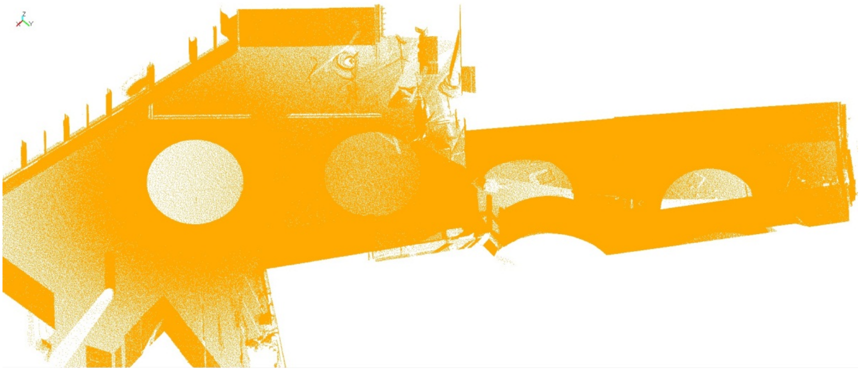

Figure 13: Coordinate point cloud from Leica C10 laser scanner

The experiments with the photogrammetry setup show that the number of coordinates is highly affected by the number of gradients in colour or texture of the measuring object. Using photogrammetry for measuring on a construction site with walls of plasterboard and floors of concrete yields few gradients in both colour and texture, is not optimal, and might possibly be improved by increasing the number of coordinates by adding contrast using some sort of markers.

The laser scanning with the Leica C10 performed by the company Mättjänst AB was the technology that gave the most information. The supplier of the measuring service provided the researchers with point-cloud data (Figure 13). The process of transforming the scan information into 3-D CAD models is a service that seems to be missing in Sweden. This supplier used a company from India to make the point-cloud to CAD transformation. What can be seen in the provided 3-D CAD model is that it seems to be simplified and information, for example about wall-floor angles other than 90°, is missing. Furthermore, measured objects such as a sheet metal sleeper on the floor whose edges are about 1 mm are represented as 5 mm-thick material in the provided 3-D CAD model from the laser scanning.

Still, there is a need to develop competence and technology to provide joinery products suppliers with methods for acquiring true as-built information in 3-D with adequate precision and with a price range and working efficiency that make it a cost-effective solution.

When to perform measuring and refine information into CAD models is also an intricate question. The product engineering and realisation require a certain lead time. Before starting production, the joinery products supplier needs spatial as-built information, but often the product environment is not ready for measuring the as-built environment. Therefore, more is needed to develop the process of supplying of joinery products to construction than simply finding a way to verify the as-built spatial information in 3-D with high accuracy, even if this is an important issue in the overall process.

4 Conclusions

Based on the experiences of the studied cases, it is evident that the process of supplying engineer-to-order joinery products to construction has potential for improved efficiency. In the studied process, violations of Lean principles are found, which is natural in an organization that does not consciously apply the principles of Lean. These violations affect the process of supplying joinery products to construction, and much of the identified waste can find its cause in these violations. All aspects of the seven wastes (TIMWOUD) have been observed in this process, and this hampers efficient use of available resources. Innovation in adopting Lean principles and management of information, supply chain, planning, and coordination is believed to be essential for improving total process performance in supplying engineer-to-order joinery products to construction.

Generally in construction, attempts at increased levels of industrialization are approached through increasing the level of prefabrication, for example in industrialized housing (Lessing, 2006). Thus, efforts are made to move construction activities from on-site to off-site, since this is believed to increase the predictability of the work on-site (Howell, 1999). This is parallel to the findings presented in this study. An increased level of prefabrication of the joinery products, decreased assembly time, and increased predictability of on-site work seem possible if the following root causes of the observed problems are addressed:

- Contractual relations
- Information standardization and communication

In the current model for the procurement of the joinery products supplier, processed information awaits the addition of further value during the business transaction, which is distancing value-adding actors from each other. A more long-term contractual relation than on project level is desirable, where more focus is on value adding through more concurrent and interactive work between those who create value in this process. This would provide for a more efficient knowledge accumulation through the value stream, since information would be shared and mutually developed. With the longer time horizon for the supplier, more interaction with prescribers, enhanced production planning, and enhanced product engineering and assembly planning increasing the level of prefabrication of the products are possible. Then much of the current under-processing could be avoided and the flow of the on-site work could increase and thus decrease the time needed on the construction site.

Information is a central part of the total process of creating engineer-to-order joinery products, often prescribed by an architect, engineered and produced in a factory off the construction site, and assembled on-site by a local contractor. More and more information about the product is accumulated before the final realisation and assembly of the product. As this process evolves across organizational borders through different individuals, information needs to be communicated in order to build up the knowledge of what, how, and when to perform value adding work for the individuals concerned. Thus there are a number of interfaces where information is exchanged and, as a result, deficiencies in this knowledge exchange have a great impact on the process efficiency.

This study has shown numerous examples of deficiencies in this information exchange through the value stream. This appears both in the supplier interface to the construction process as well as in the supply chain of the supplier itself. What is problematic is the culture of solving problems as they arise and the use only of minor resources for developing the overall process performance. The absence of root-cause analysis of problems in the process limits organizational and inter-organizational learning through the value stream, and similar problems reoccur repeatedly.

Many of the information communication problems observed within the suppliers' own processes surface during the assembly. Four major contributors to assembly inefficiency were found in the studied cases:

- Inadequate planning and coordination
- Absence or inadequacy of assembly information
- Under-processing in design and production
- Spatial uncertainties

Adopting principles of Lean production and increasing the focus on flow and reduction of variability are suggested in addressing the above-stated problems. Currently detailed tact planning of the assembly work and coordination with other on-site sub-contractors in advance are absent, which has a major impact on variability and project efficiency (Tommelein et al., 1999). Adoption of the principles of the Last Planner system (Ballard, 2000), integrated project delivery (American Institute of Architects, 2007; Forbes & Ahmed, 2011), and Line of

Balance and 4D/nD information modelling (Björnfot & Jongeling, 2007) seem to be potential innovations for this problem area.

Increased efforts of joinery product suppliers in 3-D modelling and measuring are important in avoiding under-processing and eliminating spatial uncertainties. Further use of information technology tools for increased visualisation and efficient knowledge transfer is also believed to be useful in this context.

The use of more advanced technologies for measuring the as-built environment for the joinery shows potential, but our experiences show that the accuracy of the retrieved 3-D spatial as-built model are not in parallel with the tolerances achievable in the manufacturing of the joinery products components. Thus all spatial uncertainties cannot be eliminated, even if the certainty is increased compared to the current manual methods. There is therefore a need to develop competence and technology to provide joinery products suppliers with methods for acquiring true as-built information in 3-D with adequate precision and with a price range and working efficiency that make it a cost-effective solution.

This study cannot provide the complete picture of the general situation of supplying ETO joinery products to construction. However, together with more research in this area, it can contribute to the theoretical generalisation. In the cases studied, the procurement model and information communication inefficiency are the main hindrances. How to find solutions to those problems is not clear, and prerequisites for performing suggested methods and their efficiency in this context need to be proven.

5 Future work

Research for increased efficiency in supplying joinery products to construction is the overall aim of this thesis. More research on adopting Lean principles and management of information, supply chain, planning, and coordination in the context of supplying ETO joinery products to construction is needed. An increased focus on value also puts the focus on the effectiveness of the process.

As the current design of the contractual relations and deficiencies in information standardization and communication hamper efficient knowledge creation and exchange, more research is needed on:

- How to enhance communication between the architects and the joinery products supplier in the design phase of the construction process
- How to establish more long-term contractual relations with more focus on the system performance and the application of continuous improvements for the overall process
- How suppliers can suggest and establish relational contracting (Forbes & Ahmed, 2011) with their procurers
- The development of measures for predicting, controlling, and evaluating the process performance
- How to develop continuous learning from the experiences and knowledge gained in completed projects for engineer-to-order suppliers
- The applicability of tools and theories on planning and coordination for small engineer-to-order suppliers to construction
- How to make use of ICT tools for improving the information flow through the supply chain
- How to decrease or eliminate spatial uncertainties with the use of 3-D scanning technologies
- The demand on the tolerances required on measuring equipment for eliminating spatial uncertainties for ETO joinery products
- How to increase the level of prefabrication through decreasing spatial uncertainties of the as-built environment
- How to decrease or eliminate uncertainties in the process of supplying joinery products to construction for increasing the level of prefabrication

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APPENDIX 1: INTERVIEW QUESTIONS

The structured questionnaire is exemplified by the following questions:

- **A description of the current process**
  - How does the respondent consider the character of work?
  - Could the respondent describe his/her perspective on the prescribing/realisation of a product solution?
  - What form of contracting is used?
  - What is the level of commitment of the respondent?
  - Is there a cost framework, and how are the costs managed?
  - How would the respondent describe the current culture in construction?
  - What is the respondent's vision of an optimum process?
- **Conditions for the respondent character of work**
  - How are the respondents procured?
  - How are the respondents contracted?
  - What responsibility/authority does the respondent have?
  -What experience does the respondent have?
  - How are products/projects designed?
- **Interaction along the value chain of the construction project**
  - Is there any interaction with other actors in the value stream?
  - Are there any routines for interaction?
  - With whom does the respondent interact in the construction project?
- **Information accumulation and exchange across disciplines**
  -.With whom does the respondent communicate?
  - What communication is needed?
  - What information is needed in the work of the respondent?
  - What information is needed downstream of the respondent?
  - What tools and methods are used for communication?
  - Are there any standard procedures and protocols for information exchange?
  - What is the view of the respondent on integration between the process and actors in the process?
- **Prerequisites and the need for measuring equipment**
  - Is there a need in the respondent's profession to verify spatial information?

- What techniques and technology are currently used?
- What opportunities can the respondent see in technology supplying accurate 3-D spatial information?
- Does the respondent experience any discrepancy between drawings and the as-built reality?

- **Pros and Cons**
  - What pros and cons in the actual project have the respondent experienced?
  - Could anything have been done differently?
  - Does the respondent have any ideas for improvements?
  - If any problems are perceived, what does the respondent think is the cause of them?

Paper I

Interaction in the construction process—System effects for a joinery-products supplier

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Interaction in the construction process—System effects for a joinery-products supplier

Samuel Forsman[1], Anders Bystedt[2] and Micael Öhman[3]

Abstract

Research Questions: How is the supply-chain relation between a joinery-products supplier and the construction process arranged, and what deficiencies can be seen from a supply-chain and information-management perspective? If there are deficiencies in the supply chain, what are their causes, and what possible improvements can be made?

Purpose: To contribute to the understanding of the interactions present in the construction system and their effects on the make-to-order/engineer-to-order joinery-products supplier.

Findings: Supply-chain management and information management are two areas that work poorly and cause numerous knowledge-disconnection effects. The main reasons for undesirable consequences in the process are: (1) information needs are not met; (2) competence is lacking; (3) there is a lack of activity in the gathering and mediation of information; (4) inventory buffers break the flow of value-creating activities.

Limitations: The study is limited to contributing knowledge from a single case in the north of Sweden about the effects of the present interaction level in the construction system. The main discussion is limited to the interaction between a joinery-products supplier and the construction process.

Implications: The academic implication is to contribute to the theoretical generalization for the area of construction-related joinery-products supply. The implication for industry is to gain information that will help to improve interaction and develop better production strategies.

Value for practitioners: The value for practitioners is the indication that more interaction between suppliers, originators and adjacent processes is needed. Standardized routines for interaction and more active information exchange are needed in order to decrease inventory buffers and increase value-creating activities.

Keywords: Construction, Joinery products, Secondary wood-products manufacturing, Information management, Supply-chain management

Paper type: Case Study

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Introduction

Interaction in construction involves a process in which individuals or organizations through their actions affect each other in terms of managing communication and collaboration. The traditional construction process is mainly project-based and characterized by one-of-a-kind set-ups (Vrijhoef and Koskela 2005) in which the unique characteristics come from the production set-up, site and temporary organizations (Höök and Stehn 2008). The traditional construction process is characterized by being of a fragmented nature with loosely coupled actors who only take part in some of the phases of the process (Anheim 2001). Since construction projects are often complex and involve many different actors, the communication is both comprehensive and complex (Cigén 2003). According to Cigén (2003), the main reason for interaction in the traditional construction process is the coordination of efforts and the implementation of time planning. The communication focuses on detailed questions of a problem-solving character and with a short time focus. Another significant reason for communication is to transfer information and documentation, often to inform other actors about changes, mistakes and delays. Due to the fragmented nature of the construction process, the information flow is also fragmented. Thus the communication process suffers from a meagre information flow between various actors in the process.

Construction companies work in a culture of hiding experiences and information instead of sharing them. This culture works against effective development (Polesie *et al.* 2009). For instance, Santos *et al.* (2002) claim that companies often fail to implement and maintain standardized practices due to a lack of teamwork. On the other hand, Holst (2004) states that the sharing, creation and use of knowledge across traditional boundaries is becoming more and more common. This trend, with boundary-crossing groups, is a result of the organizations being challenged to be functional in an increasingly networked and globalized world.

Supplying the construction industry with highly value-added one-of-a-kind wood products is the major business strategy of the make-to-order/engineer-to-order (MTO/ETO) joinery-products supplier studied in this case. Here make–to-order refers to new customizable products being made to order to suit specific needs. Engineer-to-order refers to not-already-defined products being engineered to fit specific needs. Further on in this text, the MTO/ETO joinery-products supplier is referred to as a joinery-products supplier. The joinery-products supplier offers products like entrances, glass partitions, doors, windows, furniture, cabinet fittings, special fittings and stairs. Supplying construction involves interactions and information flows between various actors in the construction process that define the fully customized product from the supplier. In this interaction and information interchange, mismatches occur that affect the performance of the construction system and the supplier.

In construction-related research as well as in forest-products research, MTO/ETO joinery-products manufacturing and its peculiarities in supplying construction seem limited. In the case of this study a supply process of a stair railing is studied. There are earlier examples of studies on the supply-chain management in construction (SCMC) area focusing on pre-engineered metal building manufacturing, electrical switchgear, elevators and aluminium windows (Akel *et al.* 2001; Elfving *et al.* 2002; Azambuja and Formoso 2003; Fontanini and Picchi 2004; Arbulu and Tommelein 2002). In 2010 Melo and Alves presented a work on supply chains and prefabricated wooden doors, concluding that information deficiencies and a lack of integration in the system can take away the benefits of prefabrication of joinery products. Furthermore the authors conclude that a lack of trust and preconditions leads to longer lead times.

With this background, the following research questions are addressed in this study:

- How is the supply-chain relation between a joinery-products supplier and the construction process arranged, and what deficiencies can be seen from a supply-chain and information-management perspective?
- If there are deficiencies in the supply chain, what are their causes, and what possible improvements can be made?

The study was conducted from a systems perspective, meaning that the focus is on the entire process from design to assembled product. However the scope is mainly from the joinery-products supplier's view. The study emphasizes the interaction between a joinery-products supplier and the construction process. The purpose is to contribute to the understanding of the relations and contacts between the construction process and the joinery-products supplier. The study was conducted in an ongoing on-site construction project in 2009, and the information derives from this specific studied case. The study is limited to contributing knowledge from a single case about the effects of the present interaction level in the construction system. The main discussion will be of consequence for the interaction between joinery-products suppliers and the construction process.

Theory

Traditionally manufacturing can be described as a value-adding process (Bröte 2002) in which raw materials are transformed into finished products that the company sells (Jackson 2000). Koskela (1992) compares the conceptual basis of conventional construction and the new lean production philosophy. The conventional production philosophy of conversion of input to output is restricted to looking at production as a set of operations that are controlled operation by operation and improved periodically. Lean also takes into consideration the process flow with respect to waste and customer value. Thus lean adds the dimension of the interaction between the operations in the production. Koskela (1992) finds that the construction industry is truly conversion-oriented, as previously observed in manufacturing. Because of that, construction is unable to control the amount of non value-adding activities (waste) and even less able to manage continuous improvements. Value-stream mapping (VSM), presented by Rother and Shook (2003), is a method used in analyses of the value adding in supply chains in construction. For example, Arbulu and Tommelein (2002) show through VSM that the waiting time (inventory buffers) is a significant contributor to the lead time in the analysed supply chain. Vrijhoef *et al.* (2001) contend that a major part of the inefficiency and problems in construction is related to supply-chain problems, as shown in Figure 1.

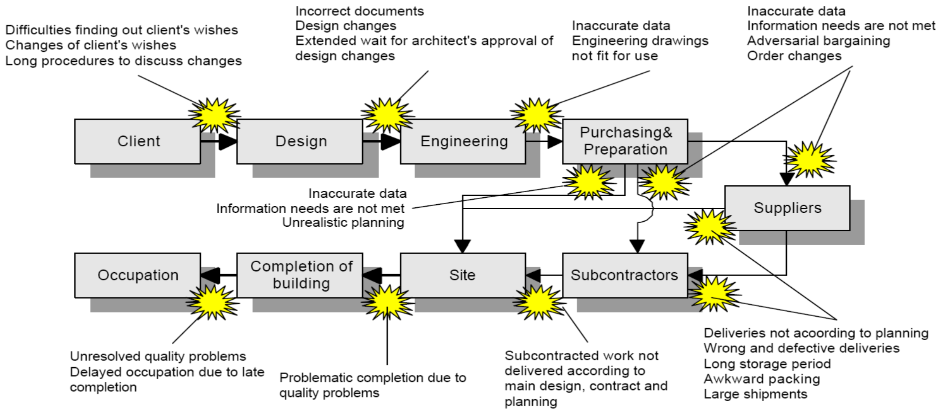

Figure 1: Generic problems in the construction process (Vrijhoef *et al.* 2001). Reproduced by permission of R. Vrijhoef.

Traditionally, supply in construction is controlled as a series of individual activities rather than being viewed as an integrated value-generating flow, as in supply-chain management (SCM). SCM issues are typically related to information and communication problems through the phases and contributors in construction. SCM is closely related to the supply model used in lean production.

There is evidence of benefits for practitioners from close relationships in supply chains that together focus on adding value to a process faster than adding cost (Lamming 1996). When the focus on value and cost accumulation through cross-organizational boundaries is limited in construction, the development of the interaction interface between the actors in the construction supply chain is still inadequate (Polat and Ballard 2003).

Vrijhoef (1998) finds that problems occurring in the supply chain are mostly caused by other actors or part processes in the earlier stages of the supply chain. Pollat and Ballard (2010) find that problems for the entire value chain start as early as the design phase. According to Koskela (1992) attempts to develop the construction process are hampered by traditional design, production and organizational concepts and by the peculiarities of construction. The one-of-a-kind nature of projects, site production, temporary multi-organizations injecting new members into the construction interaction chain and regulatory intervention are known peculiarities of construction. Problems caused by these peculiarities are a lack of feedback cycles where the culture is to hide information and experience, flow configuration difficulties where the different part processes are not well suited to each other, variability problems caused by a low level of standardizations, problems in the communication of knowledge across organizational boundaries and a lack of accumulating improvement in processes. These peculiarities affect the studied cases when conducted in a traditional way. As early as 1992 Koskela asserted that by implementing structural solutions, such as minimizing the one-off content of projects, the on-site content of material flows and the temporary organization interfaces, the effects of the peculiarities of construction can be avoided or at least minimized.

Improvement across the conventional organizational boundaries can be stimulated by long-term relationships or partnerships between actors in the construction process. Thus one minimizes the work of finding routines for cooperation and interaction with new members and can focus on improving the routines for interaction. For this task there is a need to reconceptualize construction as flows and change the way of thinking. According to Azambuja and Formoso (2003) there are cooperation problems—a lack of coordination and integration between agents—in the construction process. For example Bildsten *et al.* (2010) suggest that value-driven purchasing is better than market-driven purchasing. According to Lessing (2006) increased productivity depends on how well a company succeeds in changing focus from unique projects to continuous processes.

Research methods and empirical results

To understand the interaction in the studied process, the case was evaluated from a systems perspective. The study focuses on interpreting and understanding the interaction practices and processes of the actors involved in the case. The study was carried out as a case analysis with a hermeneutic qualitative approach with the purpose of enhancing the knowledge of how the information and interaction between different actors appear and what practices apply. Case analyses are appropriate when the research problem requires understanding of complex phenomena that are not controllable by the researcher (Yin 2003). Data were collected through semi-structured interviews, meaning that an interview guide was developed prior to the interviews, but questions outside the guide were also asked during the interviews. This was in order to enhance the understanding of the process and the interactions. According to Bell (2000) the structured interview strictly follows a guide, the semi-structured interview follows the guide but the interviewer can ask questions outside the guide and the unstructured interview can bear more of a resemblance to a conversation about an area of interest. Beyond the interviews with the involved actors, project documents were used, such as contracts, drawings, organization charts and cost estimates, to verify and to understand more about the interactions and the process. Observations were also conducted on the building site. Lucko and Rojas (2010) suggest that to establish validity, at least face validity, it is useful for the construction industry to use semi-structured interviews. The interviews were semi-structured, and the study was built on 18 interviews, each of which was recorded and supported with detailed notes. The observations were documented in pictures and notes. The documentation regarding the studied case was copied and filed. Each interview, document and observation produced data, but it is the combined results of the interviews, documents and observations that generate the significant contribution to the analysis. Yin (2008) discusses triangulation as a method for validation; in short triangulation means that the studied object is looked at from different angles. In this case we chose to use interviews as one way and documentation and observation as a second way, and used three researchers to look at the same material, ending up with the same conclusions, to build up the internal validation through triangulation. The study aims to contribute to the theoretical generalization in the construction area. Accordingly, the study is not a far-reaching study over time and can at its best give a momentary picture of the reality that applied at the time of the interviews, the documents and the observations, as well as a reconstruction of the development up to that point. The respondents were chosen for their specific knowledge and position to provide relevant information about the process.

The studied joinery-products supplier is an association of a production company and a sales company. The sales process in the traditional construction process means that the customers send out quotation requests to possible subcontractors in two cases: (1) when the contractor is calculating for a possible project and is supposed to make a quote for a future proprietor in the early stages of the product determination stage; (2) when the customer has received a project from the future proprietor, i.e. in the late stages of the product determination. This procedure in the construction process means that a project is processed twice before a contract is signed between the customer and the studied organization. The quotation requests are often guided by quite detailed and complex regulations. Apart from the regulations, there are often varying degrees of detailed definitions and specific demands that are open to interpretations from both sides.

The studied case builds on the experiences of a manufacturer of joinery products supplying an ETO wood product to an on-site construction production of a new office building. The process began with a quotation request for a twelve-floor continuous stair railing in solid wood, with some complexity prior to production (Figure 2). The complexity involved verification of the as-built geometry of the stairs and corresponding 3D modelling necessary to control the numerically controlled machinery in manufacturing. Already small deviations between drawings and as-built would sum up to a substantial error if not accounted for by the joinery manufacturer.

The joinery-products supplier is an association of a production company and a sales company. The construction project is represented by the client, architect, constructor, construction coordinator and construction contractor. The construction contractor is the buyer who is ordering the products from the joinery-products manufacturing organization.

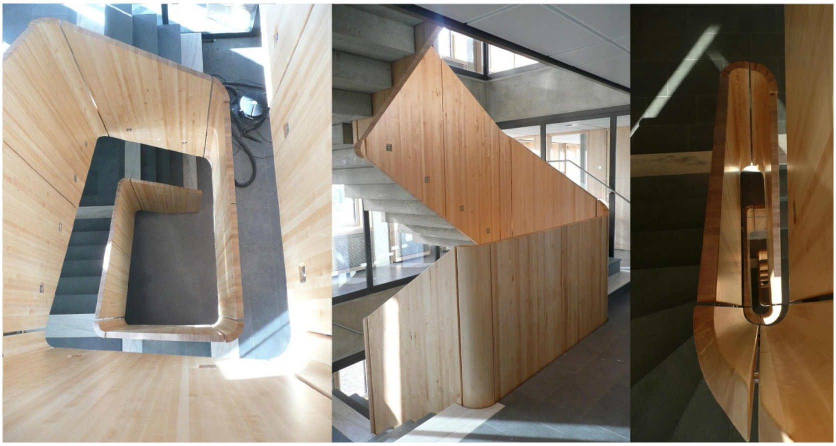

Figure 2: ETO product in the studied case

The construction process interviews

Client

The client, KJ, expressed that a key to the experienced success in the project is to use organizations that are not slim on personnel, as both the construction contractor and the client organization. Communication during the project was through a centralized database with a web interface making the information remotely accessible. Email and personal meetings are also considered important communication channels improving the interaction. Making subcontractors and suppliers contribute the solutions early in the process also stimulates interaction. KJ stated that they have come a long way with the web-based project sites, though outside suppliers have not had access nor asked for it. Further optimization of information management is seen as an important component.

High-quality interaction is valuable and it's important to come in early in the process to achieve interaction.

To avoid a situation in which the general contractor exploits its dominant position in the negotiation with suppliers, the client applied a coordinated general contract for the project in this particular case. The client thus procured some of the subcontractors that were to be coordinated by the construction contractor.

Architect

According to the architects, JF, FB and JB, the main role for the architect is to interpret the client needs and translate these needs into an expression. In this process, the need for cooperation is great between the customer and the architect. It is also important that this contact has the right process timing. JF sees the direct contact between actors in the process as important for the knowledge distribution in a project, in order to fill in the details for, for example, the suppliers. JF stated that the prescribing can be detailed on visible parts of the product while other parts are mostly left to the supplier to solve. In the overall project, JF, FB and JB concluded that cooperation was built through close dialogue between the actors in the process. A problem was that not all the actors have initiated and participated in the cooperation, for example the joinery-products supplier in the studied case.

The project of the stair railing supplier was ambitious but it was done without dialogue.

There were shortcomings in the relations between the consultants and also between other actors in the construction process. Still, the overall project is seen as a good example with well-managed interactions. JF and JB do not see effective alternative tools for interaction that surpass dialogue. The interaction outside the dialogue is the communication of layouts and visualizations. This interaction is mainly managed digitally. JF believes that each part process, for example different design areas like electricity or HVAC, needs self-control with a system focus and calls for an individual or a function that focuses on smoothing the interaction between various actors in the process. The main areas for development in the construction process, as seen by JF, FB and JB, are openness, cooperation and feedback-developing actions and tools supporting interaction.

Engineer

The engineer, KH, described the main role of the engineer as being to convert the architect's expression into construction drawings. This work is performed in cooperation mainly with the client and the construction contractor. The level of engineering in the details varies; the engineer does not have competence in every type of product, and therefore some things are left for the supplier to solve. According to KH, the main interaction with other contractors occurs in planning and construction meetings. The problem according to KH is that there are many actors involved, and they do not all think of commenting on or sharing information.

Cooperation and coordination between the actors in construction is important, but maybe the most important coordination is between consultants in the design.

KH says that there should be coordination meetings earlier in the process. A problem with meetings is that all have to be present at one location. Therefore, KH calls for better communication forms.

Construction coordinator

The client organization hired an external contractor, EJ, to interact between the construction contractor and the design originators (e.g. architects, engineers, HVAC engineers). A responsibility was the coordination of all the questions raised for the originators from the contractors. This role is considered important, and the idea of this process is to assure correction feedback to design documents and two-way information transfer between the design of all the technology disciplines and construction. In practice, EJ's role evolved to coordinate design changes and the interaction between contractors and suppliers in the process and these were not defined in the role at the beginning. EJ's role also involved enhancing communication and decreasing the time from questions to answers. In the case there was a focus on choosing the best solution rather than the cheapest. EJ stated that the culture is open for cooperation, but there are given rules to follow in standardized contract regulations. There also seem to be culture-bound obstacles to initiating contact in some areas of the industry.

Weak interaction and lack of feedback result in meagre solutions.

EJ sees the optimal construction process as one in which all the design is completed before the start of construction. This seems to be hard to achieve when there are obvious lacks in the coordination between contractors in the design, leading to problems with, for example, interference in design and meagre solutions. More time and interaction in design would be needed before the start of construction.

Construction contractor

The construction contractor, HR, finds that the project was successful, but had some interaction mismatches and design conflicts.

The industry has become more professional, but there is still a long way to perfection.

The main problem areas were in drawings, a lack of coordination between actors and competence. HR reported that the production was largely conducted by following drawings, and in some cases the ability to read drawings was poor. Most of the communications on design concerned problem solving. HR calls for more dialogue and cooperation, better design, better coordination and competence development. According to HR construction is about logistics, and there are large gains to be made from finding the right individual for each task. Accordingly there must be a standardized procedure for information transfer, and all the actors must be users of that standardized procedure.

The joinery-products supplier

Sales

The sales division is organized to serve the MTO and ETO product strategy. The seller, CH, says that the desired position is relationship marketing allowing the manufacturer to interact with design in the construction project. The majority of orders come from the construction contractor. If the supplier is involved with the design, it is more seldom exposed to competition in the purchase.

Regarding interaction with construction, there's generally no or little dialogue between entrepreneurs in the preparatory stage.

In the assembly phase, subcontractors meet at the construction site and coordinate with each other. In the studied case, there was no interaction with adjacent processes, causing a need to conform to the given conditions, such as improperly positioned railing anchors in the stair. CH says that the main information carrier produced by sales is the contract and accompanying documentation that are delivered to the joinery producer. The contract initiates the process for the producer. The contract handover is performed together with a contract review that informs the producer about the project. The major issue from the sales perspective is how to obtain a faster and more accurate calculation basis in order to make competitive and profitable quotes.

The studied case had an element of uncertainty resulting in production errors affecting the production cost and flow for the assembly. CH stated that some of the errors could have been avoided with better process control.

Sales calculation

The sales calculator, JH, uses customer-supplied information to estimate the cost of the product. Depending on the product complexity, there is an interaction with the producer. Despite previous experience with special projects, the character of the studied project was seen as complicated regarding ensuring the as-built geometry of the object and the 3D modelling needed. The quotation request sent from the customer consisted of drawings that showed a plan and an elevation, but no actual details. Drawings are seldom mediated in Computer Aided Design (CAD)formats. It is customary in the construction industry not to define in detail and to leave design parts to the supplier to solve. Despite the lack of information, no architect contact was initiated. Errors in the 3-D modelling carried out by the joinery producer were not detected, and control of the producers' modelling is not a responsibility of the sales calculator in the current interface between the sales company and the producer. JH reported that the producer has that responsibility. The errors gave incorrect product deliveries that affected the assembly.

With a totally new product, the development cost is difficult to cover in a single project.

More difficult projects are strategically important since they often generate orders for other products as well. According to JH, the use of 3-D modelling could be useful in automating the generation of useful assembly information, which normally is not done. The assembly is considered to have performed well and contributed to developing the product from the assembly perspective. The conceptual idea of the product attachment is considered to have worked almost flawlessly—only minor adjustments were required on-site.

Production

CF and PW, in production, claimed that the production preprocessing in this project was a challenging 3-D modelling task conducted under time pressure that required new modelling knowledge. PW realized that they needed more modelling competence and that the manner in which sales and production were to support each other in such a case was not defined.

Sales calculates the project, and they hold the information.

The magnitude of the project was not fully grasped when the project was estimated, and key problems in the modelling and production method were underrated. The initiation of the project at the producer was late due to a late order. The need for new manufacturing methods required more man-hours than estimated. Machine limitations were not accounted for in the estimate, and no supporting systems were available to automate such information. Modelling errors were made that could have been avoided through better interaction with sales. Interaction with construction was limited, and no interaction with the architects was initiated. Interaction with assembly was a continuous and iterative process, developing both manufacturing and assembly processes. The main information carrier was the contract and its drawings. CF and PW see information and information transfer as a topic for improvement in the organization. Currently no standardization is used to assure the quality of information. How manufacturing and assembly interaction and information exchange will perform is a from-time-to-time developing model. Assembly needs information to understand the assignment, but what information and from whom needs to be defined in every specific case.

Assembly calculation

OH, the assembly project manager, plans and calculates the on-site assembly of the products and interacts with the assembly contractor, construction contractor, sales and the producers to find a manufacturing method that facilitates assembly.

By working closer, probably much of the present assembly trouble could have been avoided.

That is where 3-D modelling errors caused disruption and extra cost in the assembly of the stair railing—errors that OH considers could have been avoided by interacting with the sales company with respect to the 3D modelling, but neither part initiated such interaction. Production preprocessing was considered late at the start, resulting in late material orders and late material deliveries. That, along with modelling problems, delayed the production and the deliveries to the assembly crew. Except for the errors, the assembly was considered as running smoothly. OH said that difficult one-of-a-kind projects like this are considered difficult to run profitably the first time, though they might generate orders for other products in the same construction project and show off production skills. In those projects, the order-supplied information, mainly drawings, seldom held all the necessary information for production. Interaction with the prescribing parties is generally needed, but in the current project, architect interaction was never initiated.

Assembly

The assembly was performed by a subcontractor interacting with the producer to find assembly methods and product solutions. On-site test assemblies were performed in the presence of producer and sales representatives. The test assemblies were seen as successful, and the assembly methods were developed from that test. The stair was not constructed with consideration of the anchoring of the joinery product to the stair, resulting in more time-consuming assembly.

The project has been a long journey.

Problems in the assembly were: (1) at the start, no written instructions for assembly were available; (2) problems discovered early on were still present when the assembly phase was embarked upon; (3) incorrectly manufactured components arrived at the assembly causing staff to wait in an idle state and delays in material supply. Late in the process, reference heights from the 3-D model were given to assembly, allowing easier product positioning on-site. One reason for these problems is seen to be an effect of the producer being late in starting the project. As the delivery dates were fixed, the problems increased the pressure on assembly, requiring overtime work.

Analysis and discussion

The objective was to study interaction in the supply chain in supplying an ETO joinery product to the construction process. The study was conducted from a systems perspective, emphasizing the interaction between the joinery-products supplier and the construction process. The analysis was based on interviews, on observation and also on documentation regarding the process.

The gathered information illustrates that the main negative effects are caused by the following factors: (1) information needs are not met; (2) competence is lacking; (3) there is a lack of activity in the gathering and mediation of information; (4) inventory buffers break the flow of value-creating activities. Putting the studied case in the generic perspective presented by Vrijhoef *et al.* (2001), the main factors result in the following consequences:

- Inaccurate data transfer or lack of data transfer
- On-site solutions without information feedback
- The physical distance from the construction site influences the amount of information received due to a loss of informal information channels on-site
- The distance from the construction site also influences the ease of on-site controls of adjacent environments
- Known problems are not solved because of undefined areas of responsibility
- Uncertainties both in production methods and in technical solutions
- Errors and delays, such as incorrect deliveries to assembly
- Lack of feedback except in cases where problems have arisen
- Disturbances in the process flow
- Information inventory buffers; for example, twenty-seven weeks elapsed from the supplier quote to the construction contractor's order.

In Figure 3, the studied case is illustrated with value-chain interaction problems affecting the supplier pointed out with stars. In the studied case, the relation was between the construction contractor and the joinery-products supplier. Most often, the supplier sales efforts were towards the construction contractor. Through this procedure, the construction contractor could easily disconnect the supplier from those accountable for the design. This disconnection affected the transparency of information negatively, and even worse, customer demands were filtered through yet another link in the value chain. In the studied case the information in the project database was not accessible to the joinery-products supplier. The supplier witnessed that in general, drawings were seldom mediated as CAD files, which limited information and caused duplicate work to be conducted.

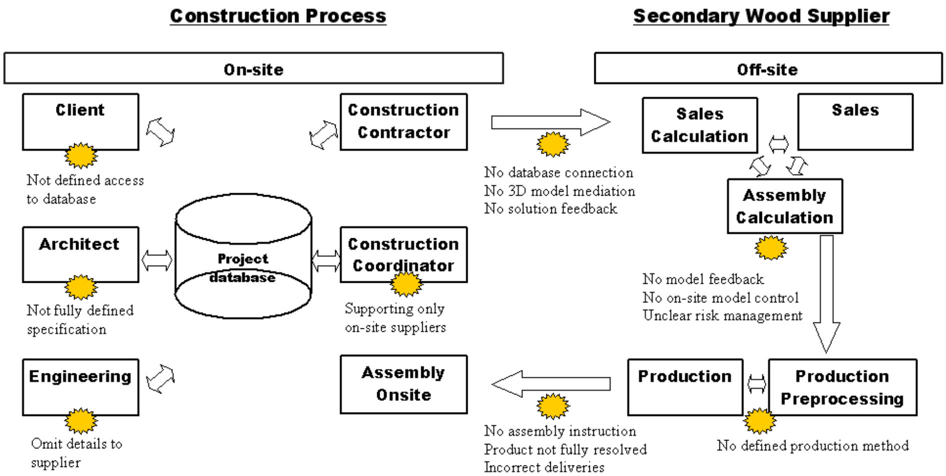

Figure 3: The customer and supplier information flow

Information needs

The manufacturing of products not fully defined by a prescriber to a fixed price is a peculiarity of this system. Originators deliberately left out undefined details for the supplier to solve, while at the same time, the supplier claimed that they produced according to defined specifications. The originators saw the suppliers as the product experts while the supplier saw the originators as the design experts. This undefined responsibility created a need for the supplier to interpret mediated information and can cause a value loss of the product.

In this case we can see disconnection effects at different levels in the process, one being the supplier's risk management when pricing. Responding to quotation requests involves estimating production costs and market prices when pricing the product. At this stage, the product is seldom fully defined by the originators at the level of detail needed for production. Estimation work is not chargeable, so the resolution of the estimation work tends to be limited. Thus the detailed product solution and production method are not made until the client's order is received.

This behaviour results in a need for a supplier–originator interaction that is not a standardized routine in the present supplier procurement model. Further, the joinery-products supplier confronts a number of product- and method-developing issues that need to be solved for every specific order. In this case, for example, the question of how to connect the corners of the stair railing to allow dimensional changes due to air humidity variations of the indoor climate needed to be answered. The culture in construction is for each party to optimize its own process, without proper routines for how and what information is needed for the next or adjacent partial process. The culture of ad hoc problem solving minimizes reflection on the desired state in a situation in favour of solving the situation at hand. Therefore, no root analysis is carried out, and the problem is likely to recur. What can be found is that there is no defined responsibility for keeping the focus on the systems perspective. Therefore, when processes are adjacent and should have an exchange of information, this is not always accomplished due to the lack of a systems perspective. The studied case shows an example of adjacent processes without information exchange, e.g. when the construction contractor cast the stair, cast-in anchor points were made for a railing but with a lack of information on where to position these anchor points. This inaccurate positioning of the anchor points resulted in extensively increased assembly time for the joinery-products supplier when the anchor points did not fit the prescribed product solution.

Competence

Most MTO/ETO joinery-products suppliers in Sweden are small-to-medium-sized organizations. As seen in the studied case the companies are high in craftsmen's skills, but low in engineering competence, and are not organized to participate in the construction design process.

The supplier displayed an inability to estimate accurately complex work not previously performed, and the production planning was further disrupted by repeating 3-D modelling already performed by the originators, causing delays and disturbances in the process.

A major part of the internal and assembly problems could have been avoided through exchange of the 3D model: information that was available, but was not shared. This is an example of the culture in the construction process that does not encourage work with standardized routines for interaction in cases such as this. One effect of this culture is that organizations need to have competencies in areas that they should not actually need to have. The information produced by these competencies should already be present this late in the process. At the same time, the competence of the originators needs support in the form of knowledge of product-specific effects and production effects of the chosen solution. The uncertainties in the supplied drawings and methods in the project together with the lack of risk management generate high risks in the price setting since the production costs cannot be fully known. In the studied case, for example, the production cost differed substantially from the calculated production cost.

Information mediation

In the studied case there was a competent client and future proprietor with skills within the construction area. The project was arranged with a web-based information platform for the actors involved in the project. Still, there were actors who were not invited to this platform, for example, the supplier in the studied case. On the other hand, the supplier did not seem to try to connect to the existing information. One reason for this behaviour is that the contractor/supplier relation culture does not encourage that practice, and the supplier was simply unaware of this information platform praxis. As a result of this disconnection, the joinery-products supplier managed engineering work (3D modelling of the stair) already performed by the originators, and with a lack of competence in some parts affecting the overall result.

Non-value adding

In Figure 4, a rough value-stream map of the total process shows the project lead time and the presence of inventory buffers that resulted in a major time span between the design and the ETO joinery production (data supplied by the client, joinery sales and joinery production and through observations). The time span between the preliminary quotation request and the product order was 96 weeks (27 of these weeks were between the quote and the order). During this time span, the major focus and efforts were invested in the business transaction rather than value adding to the product. When the final product design was left to the supplier to manage, this time span limited the supplier’s possibilities to interact with the client due to the narrow time (24 weeks) to design, produce, deliver and assemble the 109 wooden elements of the ETO product.

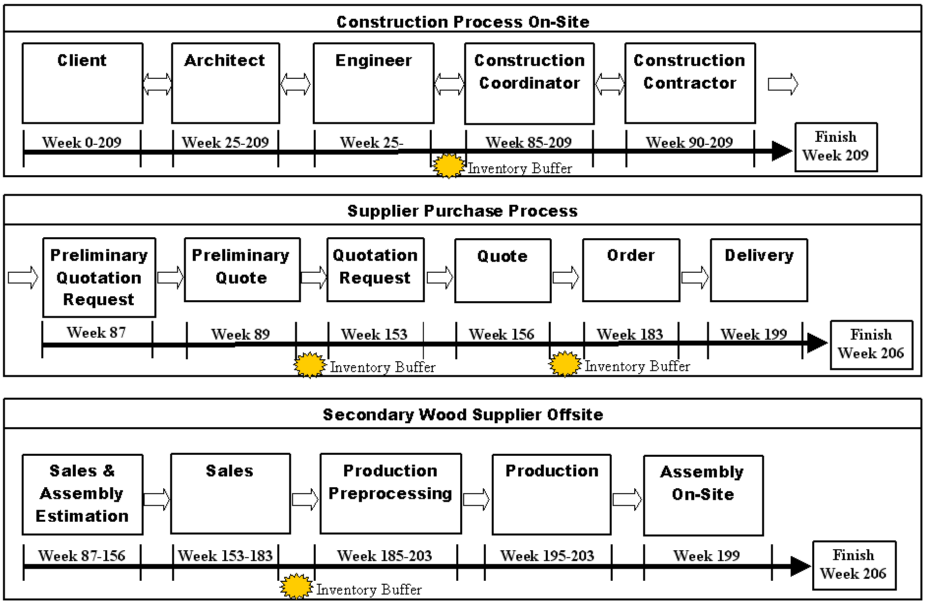

Figure 4: Timeline of the total process

The production of this ETO product involves a minimum of inventory buffers of finished goods. As soon as the first batch of finished good is produced, it is sent to the assembly personnel at the construction site for final testing and assembly if correct. If the assembly shows that the product and its design are correct the production continues with small batches that are shipped to the assembly continuously.

If looking at the total process there are inventory buffers of finished goods of information present before the actual production starts. Examples of this information are the prescribing documents of the originator, preliminary quotation request, preliminary quote, quotation request, quote and order that are stored in inventory buffers. Prescribing documents are produced early in the process and are used both in the business transaction of the ETO wood product as well as in the production preprocessing, though there is no real reviewing of the prescribing documents for the ETO wood product until the production preprocessing. The time between the preliminary quote and quotation request, and between the quote and the order, are the inventory buffers with the highest impact. After the order has been placed it is stored in an inventory buffer until the supplier can fit the order in to the production.

As seen in the study of the case, the procurement involves extensive work on estimating for the joinery-products supplier. The model for procurement also involves competition for suppliers. Thus the work of estimating costs is undertaken by several competitors in every project. There is no culture of long-term relations in the supply of joinery products. Unlike the general contractor, suppliers have a double quotation process.

The cost of making unsuccessful quotations must be covered by orders that successfully go to completion, and this tends to increase the general price level.

Summary

These findings connect to experiences found in other case studies of the supply chain in construction, e.g. Elfving *et al.* (2002) and Melo and Alves (2010), in which a lack of system view, lack of knowledge of dependencies, lack of trust, lack of consideration of preconditions etc. are a hindrance to significant improvement of the SCMC. As we see the best solution of a different model for procurement of the supplier integrating with originators would be desirable in construction. A starting point for a supply chain model in the MTO/ETO joinery products supplier would be the co-makership model between contractor and supplier as described by Vrijhoef (1998). Such a model would avoid the procurement in every single construction project and the focus could be on adding value faster than costs through joint efforts and winnings.

However the current business culture in construction is a hindrance to the joinery-products supplier already joining the construction process in the design phase. Therefore one suggestion would be to improve the standardization of the interfaces between the actors in the construction value chain.

Conclusions

As shown in this study, interaction is interfered with by poorly defined interfaces and a lack of standardizations and inventory buffers are distancing the actors in the value chain from each other. One solution to the problems that occurred could be to agree on the supplier interfaces with the contractor organization, but also with the architect and the client. This calls for different behaviour in construction towards the suppliers, and more integration of contractors and suppliers is needed to progress towards a model in which all the parties strive towards a common goal.

The case findings show that supply-chain management and information management are two main areas that work poorly, causing numerous knowledge disconnection effects for an ETO joinery-products supplier in construction. From a systems perspective, the most harmful reasons are:

(1) Information needs are not met;

(2) Competence is lacking;

(3) There is lack of activity in the gathering and mediation of information;

(4) Inventory buffers break the flow of value-creating activities.

In this case gains could have been obtained by:

- More interaction between supplier, originators and adjacent processes
- More standardized routines for interaction
- Higher activity in searching for and mediation of information
- Decreasing system-dependent inventory buffers and using time for value-creating activities

We therefore suggest improving the standardization of the interfaces between the actors in the construction value chain, starting with the most adjacent downstream actor (customer) in the value chain. This would lead to an improved information flow in the value chain. Our future work will continue with the MTO/ETO joinery-products supplier perspective in relation to improving internal processes in terms of lean values and information flow. Supporting the process with as-is 3D measurements and efficient mediation of that information is part of that research.

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Paper II

Need for Innovation in Supplying Engineer-to-Order Joinery Products to Construction

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Need for Innovation in Supplying Engineer-to-Order Joinery Products to Construction

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Abstract

Purpose – The construction industry has been criticized for not keeping up with other production industries in terms of cost efficiency, innovation, and production methods. The purpose of this paper is to contribute to the knowledge about what hampers efficiency in supplying engineer-to-order (ETO) joinery-products to the construction process. The objective is to identify the main contributors to inefficiency and to define areas for innovation in improving this industry.

Design/methodology/approach – Case studies of the supply chain of a Swedish ETO joinery-products supplier are carried out, and observations, semi-structured interviews, and documents from these cases are analysed from an efficiency improvement perspective.

Findings – From a Lean thinking and information modelling perspective, longer term procurement relations and efficient communication of information are the main areas of innovation for enhancing the efficiency of supplying ETO joinery products. It seems to be possible to make improvements in planning and coordination, assembly information, and spatial measuring through information modelling and spatial scanning technology. This is likely to result in an increased level of prefabrication, decreased assembly time, and increased predictability of on-site work.

Originality/value – The role of supplying ETO joinery products is a novel research area in construction. There is a need to develop each segment of the manufacturing industry supplying construction and this study contributes to the collective knowledge in this area. The focus is on the possibilities for innovation in the ETO joinery-products industry and on its improved integration in the construction industry value chain in general.

Keywords – Construction, Joinery production, Engineer-to-order, Innovation, Lean, Information modelling

Paper type – Case study

Introduction

The construction industry has been criticized for not keeping up with other production industries in terms of cost efficiency, innovation, and production methods (Brege *et al*., 2004). Innovations that decrease the cost of building production and alterations have gained much attention in the research community and media due to their effect on the prices of living and working environments. Schumpeter (1934) claims that "*Innovation changes the values onto which the system is based*". Aouad *et al*. (2010) define innovation in more general terms as "*the creation and adoption of new knowledge to improve the value of products, processes, and services*". What is interesting here is how the different aspects of innovation are linked together. Product innovations are likely to affect both the process and services, and in the same way process innovations are likely to require product and/or service innovations. "*Much of construction innovation is process and organisation-based*" (Slaughter, 1993). This reflects that construction is a mature industry where competition is mainly based on price (Utterback and Abernathy, 1975). Pries and Janszen (1995) state that larger organisations have an advantage over smaller firms in making use of the results of process innovations. This is reflected in the success of the Japanese construction industry, which has been able to achieve a customer orientation, efficient R&D organisation, and good vertical integration. The long-term strategy that the Japanese often practice in relationships between contractor and suppliers is not common in procuring engineer-to-order joinery-product suppliers in the Swedish construction industry (Forsman *et al*., 2011). Ozorhorn *et al*. (2010) stress that "*in construction successful innovation often requires effective cooperation, coordination and working relationships between the different parties in construction projects*". Further, Rutten *et al*. (2009) stress that in construction successful innovations are shown when working across inter-organisational boundaries.

In the manufacturing industry, the development of Lean and adoption of its principles has truly been an innovation (Lewis, 2000; Schuh *et al*., 2008). This is currently being spread to many other areas of society, for example health care (Brandao de Souza, 2009) and construction. In applying the principles of Lean production there is a need to understand the prerequisites of the environment to which one wants to adapt the principles. In construction this has been a research area in its own right, with influential researchers such as Koskela (1992, 1997, 2000, 2004), Vrijhoef (1998, 2000, 2001, 2005), Ballard (1994, 1998, 2000, 2006), and Howell (1995, 1999).

The development of production processes by adopting Lean principles in construction is still in its infancy, which is also noticeable among many of the suppliers in construction (Melo and Alves, 2010; Fontanini and Picchi, 2004; Polat and Ballard, 2003; Elfving *et al*., 2002). The mass-production origin of Lean seems to be a restraint for the adoption in this on-of-a-kind type of industry. A common situation in construction is that there are a number of sub-suppliers of products or services to a main contractor supplying the construction to the client. Aouad *et al*. (2010) stress that due to the contractual nature it is common for each party to seek to mitigate its own costs and risks by passing them on down the supply chain, which is seen to have a hampering influence on innovation in construction. As the construction process is characterised as being one-of-a-kind project set-ups (Vrijhoef and Koskela, 2005), this is also reflected in the procurement of sub-suppliers where long-term relations are limited.

The process of supplying the construction industry with highly refined one-of-a-kind wood products is what's been examined in this paper and more specifically an organisation supplying joinery products using a mixture of concept-to-order and design-to-order (Winch, 2003) production strategy. This strategy means that engineering is required in the supplying of these joinery products and consequently these are considered as engineer-to-order (ETO) joinery products. Here, "ETO" refers to uniquely designed products being engineered to fit specific needs. Henceforth "ETO joinery products" are referred to as "joinery products". The joinery-products suppliers offer products like entrances, glass partitions, doors, windows, interiors, cabinet fittings, special fittings, and stairs. Joinery products are more prefabricated than general on-site construction work but there are still limitations on the degree of prefabrication achieved in the supplying of joinery products. In the supply of joinery products, Forsman *et al*. (2011) show that the one-of-a-kind procurement model is a hindrance to effective information transactions – in both time and quality – between prescribing stakeholders and the joinery-products supplier.

With this background the purpose of this paper is to contribute to knowledge about what hampers efficiency in supplying joinery products to the construction process. The objective is to identify the main contributors to inefficiency and to define areas for innovation in improving this industry. Lean principles are used as an analysis tool, considering waste that hampers process efficiency. The main discussion will be on what wastes occur, their root causes, and suggestions for innovation through Lean principles and information management.

The study is limited to determining the perceived and observed problems in the joinery process studied, from quotation to assembled product. The study was conducted in one organisation but comprises two cases and is performed from a sub-supplier perspective. The study show Swedish cases and thus represents that specific cultural situation. Despite this many of the examples found in research literature also seem to be applicable to the Swedish construction culture.

Lean Principles

Based on the studies of Toyota, Womack *et al*. (1990) identified a culture and way of thinking in what they call Lean production. The focus on customer value and elimination of anything that does not add value (i.e. waste) is central to the philosophy of Lean. The Toyota engineer Taiichi Ohno identified seven types of waste that were later used under the acronym of TIMWOOD. The seven wastes that can be applied to any process are: unnecessary *transport* of goods, *inventory* of parts to be completed or finished products waiting to be shipped, unnecessary *movement* of people, unnecessary *waiting*, *over-production* of items not needed, *over-processing* with unneeded steps, and making *defective* products (Womack and Jones 2003).

Liker (2004) presents fourteen management principles used at Toyota that are seen to reflect the core of the Lean philosophy. The Lean principles relate to a higher objective of reducing or eliminating wasteful activities in a process as a means of increasing the share of value-adding content. The use of Lean principles in several areas, including construction, has been explored in the literature by, for example, Koskela (1992), Ballard and Howell (1998), Tommelein (1998), Howell (1999), and Höök and Stehn (2008). Different aspects of cultural behaviour in construction are seen to hamper the adoption of Lean principles, primarily the one-of-a-kind projects, site production, and temporary organisation. Howell (1999) claims that the evidence of waste in construction in the terms of Ohno is overwhelming. Waste in those terms is also evident in more recent studies of the construction industry (Polat and Ballard, 2003; Sandberg and Bildsten, 2011).

Supply chain management is a Lean principle, where work across inter-organisational borders is coordinated and optimised to enhance system production efficiency. In construction the supply chain is highly fragmented and the procurement model in the industry has been seen as hampering innovation in the cross-organisational cooperation (Vrijhoef, 1998; Aouad *et al*., 2010; Melo and Alves, 2010). There is a shared opinion that supply chain integration can be seen as a means of improving the manufacturing process in construction, especially if Lean principles are incorporated (Vrijhoef, 1998; Aouad, 2010; Sandberg and Bildsten, 2011).

More recently supply chain coordination mechanisms in construction have been investigated in relation to waste generated from a Lean perspective (Sandberg and Bildsten, 2011). This means that measures are taken to identify waste generated in the interaction between activities, functions, and organisations. The importance of this area in construction has already been identified by Howell (1999): "*Managing the interaction between activities, the combined effects of dependence and variation, is essential if we are to deliver projects in the shortest time*." However, increased understanding of the coordination mechanisms is fundamental in managing interaction in the supply chains of construction.

In Lean there is a strong focus on process flow and synchronisation of merging flows. A means of achieving this synchronisation is the tact time. This area has been addressed as a problem due to difficulties in planning construction projects because of unpredictable work releases causing variability in work flow. Ballard's *Last Planner* technique (1994) is an approach to the application of Lean thinking to this problem in construction.

Information Modelling

Coordination between the different actors in the supply chain is the core issue in the improvement of construction performance. Xue *et al*. (2005, 2007) state that there are many inter-organisational problems such as inaccurate information transfer and wrong deliveries in the supply chain that result in poor construction performance. To overcome these problems Xue *et al*. propose the Internet as a suitable platform for coordination and integration in construction supply chains. Rework, quality issues, delays, forced production, and so on are some of the problems that occur during on-site construction. These problems derive from poor planning and insufficient control mechanisms of the construction process (Björnfot and Jongeling, 2007). Zwikael (2009) points out the importance of making a thorough project plan with clearly defined project activities in order to improve the project performance.

The Last Planner is a production planning and control system used in projects to improve the performance of the construction. By increasing the reliability of the work/material/information flow and decreasing waste in terms of time/money/variability in the project, customer value is increased (Cho and Ballard, 2011; Ballard, 1994, 2000). A project can be viewed as a temporary organisation of multiple stakeholders, and achievement of the project objectives requires integration between the various actors (Turner and Müller, 2003). Construction projects involve actors from different areas of construction who work together to design and construct the common project goal. This collaborative effort requires effective communication of project information between these project participants (Anumba *et al*., 2008). In a construction project the different actors involved have decisive roles based on the information provided or communicated to them. Thus, information has to be disseminated effectively between the actors involved in the construction project. The productivity of the project will increase through better information flow (Titus, 2005). Integrated Project Delivery (IPD) is a trust based collaborative effort between the key participants in a construction project. Through an IPD contract the participants share the risks and rewards through transparent information and a concurrent process, maximising the value for the client (American Institute of Architects., 2007).

Building-information models (BIMs) are a tool for generating and managing building data through the use of CAD and ICT tools. A BIM contains spatial information, material properties, and so on and allows different actors to exchange and update information (Lee *et al*., 2006). Modern BIM tools are becoming more powerful by using parameterised models, where objects are geometrically linked together. According to Eastman *et al*. (2011) ETO producers might be the biggest beneficiaries of BIM in the construction process. The benefits come from fewer design errors due to virtual constructions, more accurate planning for installation using 4D CAD, and improved pull flow due to faster production of drawings.

Concurrent engineering, a method where product and production development is performed in parallel, has been found to yield shorter lead times and higher quality products compared to sequential engineering (Sohlenius, 1994). Concurrent engineering is seen as a tool to decrease the fragmentation in the construction industry (Love *et al*., 1998), which is known to be extensive in construction. Karlsson *et al*. (2008) followed construction cases in Europe and the US where concurrent engineering methods were used and found substantial time savings. The study also showed benefits in information exchange, communication of information and documents, and improved quality.

Björnfot and Jongeling (2007) combined Line of Balance (LoB) with 4D CAD to streamline the flow of resources during construction. LoB is a scheduling tool that shows at which location and when in time a task is to be performed and how long time it will take to complete. 4D CAD is used as a visualisation and analysis tool to evaluate and optimise the production plan and avoid clashes. Rwamamara *et al*. (2010) investigated 3D and 4D CAD visualisation techniques for planning construction from a health and safety aspect. 3D and 4D CAD not only makes a better planning tool compared with 2D CAD but also decreases poor ergonomic posture and increases the safety of workers. They also found that there was a higher degree of collaboration between the different actors of the project because of the collaborative effort to create safer workplaces. Further advocacy for 3D over 2D was done by Santos and Ferreira (2008). Their studies provide compelling evidence of greater efficiency and efficacy in the design coordination of mechanical, electrical, and plumbing systems in construction.

Literature Summary

Much of the innovation in construction is process and organisation based and generally larger organisations have shown an advantage over smaller firms in making use of the results of process innovations. In manufacturing the development of lean and adoption of its principles has truly been an innovation that also has been spread to other areas of society, for example health care and construction even if the extent is more limited in the construction industry. Still when studying the supplying joinery products to the construction industry, the adoption of Lean is limited and the prerequisites for doing so need to be investigated. The Lean principles relate to a higher objective of reducing or eliminating wasteful activities in a process as a means of increasing the share of value-adding content. The Toyota management principles presented by Liker (2004) and the seven types of waste defined by Taiichi Ohno are used for analysing the studied process in this work. Further different kind of information management tools and theories are seen as potential improvers for the situation in supplying joinery products to the construction industry.

Research Methodology

This study focuses on gaining a detailed understanding of the practices and obstacles in supplying joinery products. The focus in this work is on potentials for efficiency innovation in the process of supplying joinery products. With the focus on main contributors to inefficiency and to the definition of areas for innovation, what wastes occurring and their root cause the questions on why and how emerge. These questions are closely connected to the hermeneutic data collection methods. The emerging of how and why questions resulted in choosing interviews, documents and observation as the research method, when they were seen as superior to other methods with the objective stated. The studies in this work were carried out as case analyses with a qualitative approach; the purpose is to enhance knowledge of what problems and why problems arise in the studied process and how the studied process tentatively could increase its process efficiency. According to Yin (2003) case analyses are appropriate when the research problem requires understanding of complex phenomena that are not controllable by the researcher. The study covers the process from quotation through order, production pre-processing, and logistics to the final product assembly on the construction site. Special attention has been paid to the assembly on-site since it is assumed that the causes of many of the problems occurring in assembly can be found upstream in the supply chain.

Studied CasesThe joinery-products supplier studied is a Swedish association consisting of 11 production companies and a co-owned sales company. The target market is Sweden and Norway, but the intention is that Europe should be the operating market. The joint turnover is about €50 million and the association is seen as a major actor in its field. According to Forsman et al. (2011), the sales process targets the traditional construction industry, meaning that construction contractors send out quotation requests to possible suppliers in two cases: (1) when the construction contractors making calculations for a possible project and is supposed to carry out a quote for a client in the early stages of the product determination stage; (2) when the construction contractors received a project from the client, that is, in the late stages of the product determination. In both cases the quotation request is sent to several competing suppliers with no compensation for the work involved. The quotation requests are often guided by quite detailed and complex regulations. Apart from the regulations, there are often varying degrees of detailed definitions and specific demands that are open to interpretation by both sides.

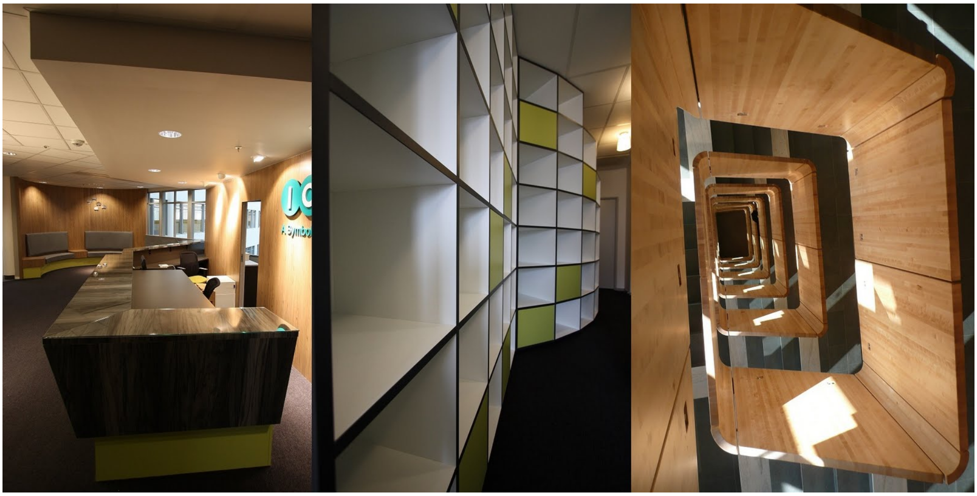

Figure 1: ETO joinery products from the case studies.
From left: a reception and seating area, a shelf system, and a 12 floor massive wooden railing.

Figure 1 illustrates the products of the cases studied, which involve the supplying of joinery products to: (1) an alteration project in an office building and (2) the construction of a multi-storey building. The two cases involve three different production companies using the co-owned sales organisation. The production companies are the product owners and thus have the responsibility to develop and manufacture the ordered products and carry the risk of the project. The sales organisation makes the deal at a percentage of the sales value and engages assembly contractors.

Data Collection

Data were collected through interviews with employees, documentation, and observation within the organisation. The following question areas have been guiding:

- A description of the current process
- Conditions for the respondent character of work
- Interaction along the value chain of the construction project
- Information communication, accumulation and exchange across disciplines
- Prerequisites and need for measuring equipment
- Pros and Cons of the project as experienced by the respondent

The interview respondents were practitioners in construction projects procuring the joinery products in the studied case and actors in the value stream of supplying those products. The respondents were chosen for their specific knowledge and position to provide relevant information about the process. Among the respondents there was: 1) the client procuring the construction project, the architects of the project, 2) the site manager of the construction contractor, 3) the construction engineer, 4) the client contracted construction coordinator, 5) the construction contractor procurer of suppliers, 6) the construction contractor surveyor, 7) the construction contractor staff realising the environment adjacent to the joinery products, 8) the sales manager of the joinery-products supplier sales organisation, 9) the sales calculator of the joinery-products supplier sales organisation, 10) the assembly procurer of the joinery-products supplier sales organisation, 11) the production manager of the joinery-products supplier, 12) the production pre-processing of the joinery-products supplier, 13) the manager of the contracted assembly contractor, and 14) the staff of the assembly contractor performing the assembly. The objective of the interviews was to enhance knowledge of how the process appears and how the organisation was arranged. In addition, the interviews focused on how the organisation relates to the surrounding actors. On-site observations were performed during manufacturing in the production facilities, during surveying, and extensively during assembly, and have been documented through notes, photographs, and audio recordings. The depicted scenes give an opportunity to reflect on specific situations in retrospect. Results from the interviews, observations, and documents have been used to produce a model of the information flow and problems arising within the project. This model is described in the results section of the paper. The information flow of the internal process of the company has been analysed through a Lean perspective. To improve the productivity of joinery-product companies, ways to innovate in the internal process through Lean principles, modelling of information, supply chain planning, and coordination have been explored. An overview of the research design is outlined in Figure 2.

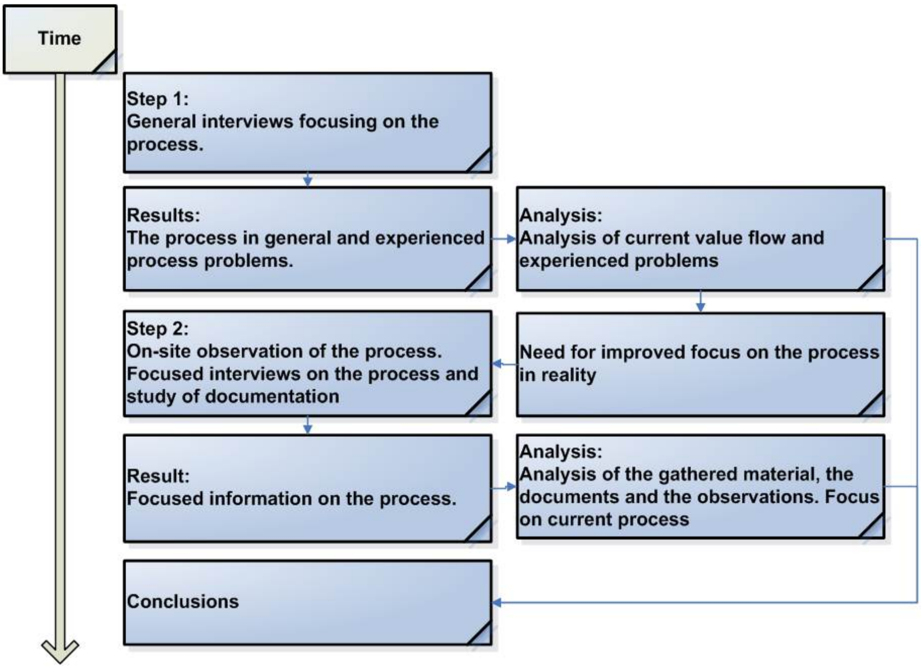

Figure 2: Research design

The first empirical evaluation was achieved through general interviews focusing on the internal process comprising an interview guide of 33 questions with a focus on describing the process. This guide was developed prior to the interviews, but questions outside the guide were asked during the interviews and “gemba walks” on the production floors (Womack, 2011). Beyond the interviews with the involved actors, project documents such as contracts, drawings, organisation charts, and cost estimates were distributed and studied. The respondents were chosen for their specific knowledge and position to provide relevant information about the process. These interviews produced three major results: (1) the general process could be defined; (2) the activities performed could be defined in the different process steps; and (3) the main problem issues experienced could be found. The staff members are skilled in their particular fields, but the process is not well documented. This lack of documentation makes systematic analysis difficult. Therefore, the need for documentation of the process in action emerged (Step 2 in Figure 2). According to Merriam (1994), observing a behaviour gives opportunities to make sense of a larger context and draw conclusions that the individual subjects might have difficulty noticing. Therefore observations were conducted in order to better understand the various aspects of the process. Extensive observations were made on the construction site to confirm information given by the respondents. The on-site observations also enabled gathering of information that the participants were unable or unwilling to fully disclose in interviews or through documentation. The interview guide supporting the observations in this second round was constructed with a focus on information and actions on-site.

The second round of information gathering resulted in focused information on the process. The study is built on interviews, documentation, and observations, and six researchers' views on the same study, this being a foundation for triangulation, according to Yin (2003). Each interview, the documents, and the observations produced data, but the combined results of all the interviews, documents, and observations are what generate the significant contribution for analysis. The material is studied as a whole, reduced to focus on the main questions of the paper, and then displayed in a reduced form. This study is not a far-reaching study over time, so it can at best give a momentary picture of the reality that applied at the time of the interviews, the documentations, and the observations and a reconstruction of development up to that point.

The analysis is focused on defining different types of waste surfacing in the studied cases and possible areas of innovation. The causes of these problems are analysed and generalisation of their causes is carried out using principles of Lean and supply chain management. The potential for achieving efficiency improvements and increased level of prefabrication by applying new technology, such as 3D measuring and modelling, and principles of information management are discussed.

Sampling, Validity, and Reliability

The sampling method has been selective with a touch of expert sampling when the respondents mainly have been chosen for their specific knowledge. The unit of analysis has been the process to sell and mount a joinery-product working inside the traditional construction process. The cases and the research method were chosen for their potential contribution to the overall question of this work. The study builds on 65 interviews conducted throughout the value-chain from sales to the assembled product.

Semi-structured interviews were used, conducted on-site during 2009 to 2011. Each interview, observation and document contributed to extended knowledge, but it is the combined analysis of the interviews, observations and documents that crate the significant contribution. The methodological approach has been qualitative with interviews, observations and documents as the data collecting methods. To create a reliability and validity in the work triangulation has been used, both in the use of data sources the analysis model and in the fact that multiple researchers have looked on the same material and come to the same conclusions.

Research Findings

The main objective in this paper is to define the main contributors to inefficiency and to define areas for innovation. Therefore the findings section of the paper focus on presenting different areas of the process of supplying joinery products that are seen as main contributors to inefficiency and therefore areas for innovation.

The process of supplying joinery products to construction is illustrated in Figure 3. This value stream represents the process used by the organisation in the studied cases. The study is delineated to cover the process from order to the assembly on the construction site.

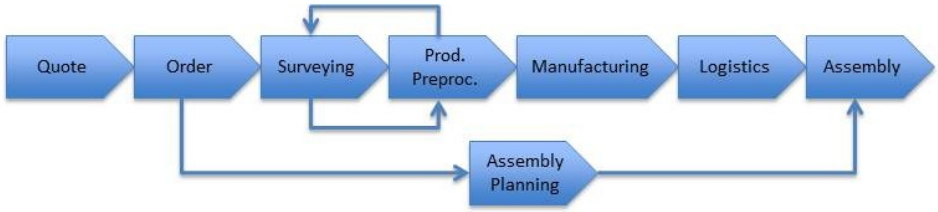

Figure 3: Value stream of the studied cases

The value stream described above shows a number of deficiencies that can be related to the management of information, supply chain, planning, and adoption of Lean principles. In the following we will present the process studied and problems observed in the joinery-products value stream that are seen to be inefficiency contributors.

Sales - Quote to Order

The sales process targets the traditional construction industry. Generally, the sales process (quote to order in Figure 3) quotes in two steps: a preliminary quote for construction contractors making a quote to a client, and a final quote to the construction contractor who receives the client order. The quotation requests are processed by the sales department that estimates cost and market value in making the quote. The products are often prescribed by an architect who visualises the client needs and the quotation requests are processed by a sales department that estimates cost and market value in making the quote.

This procurement process normally involves supplier competition and no compensation is given for the work of making quotes. When the sales department receives the order, accumulated information from sales is transferred to the production pre-processing section.

Procurement Processing

In the studied cases the procurement was done on a project level and took much calendar time in relation to the time used for realising the product. In the first case the procurement took 15 weeks while 10 weeks were used for engineering, producing, and assembling the products on-site. In the second case 96 weeks were spent on procurement while 21 weeks were spent on the steps from ordering to completion of the assembly. Thus in the first case 60%, and in the second 81%, of the calendar time was used for the procurement while 40 and 19% was used for creating the product in the two cases.

Related to this procurement model, there was much calendar time between architectural product definition and the joinery-products supplier product definition. Thus information was available but not further processed until the order was received. Architects have expressed a wish to communicate with joinery-products suppliers but the late procurement of the suppliers hampers the establishment of such communication and thus obstructs a continuous flow of information and a concurrent engineering approach. It is the construction contractors that procure the joinery-products supplier and need to give approval for the supplier to communicate with the architect. In the cases studied there has not been any direct communication between the joinery-products supplier and the architects.

Surveying

Since joinery production requires tighter tolerances than construction in general, provided drawings are not sufficient when defining the product before manufacturing. Further, in construction there seem to be no customary practices to verify that the built object really reflects the prescribing documents according to given tolerances in all built areas. For this reason there is a need for the joinery-product supplier to survey the built environment before the manufacturing. This currently involves manual measuring performed on-site, generally by the supplier, and represents a risk if they prove to be insufficient, inaccurate, or more time-consuming than planned for in the quote. The geometrical information is needed to complete the production pre-processing, and it is not unusual that to some extent to need to carry out the surveying more than once.

In the studied cases manual measurement techniques were used to obtain needed as-built information for production pre-processing (Figure 4). The measurements were done on a 2D basis. Wall placements, diagonals in the rooms, and doorways was seen as important to document.

The experiences of the respondents show that a majority of the construction projects still work with 2D drawings as the main information carrier. The results of the manual measuring were noted on 2D drawing printouts and then transferred to production pre-processing by physical transport of the actual drawing. Making templates using the information from the measurements is a method commonly used to ensure the accuracy of the measurements and this was also used in one of the studied cases. The making of the measurements on-site required coordination with the construction project. It is not unusual to perform measurements on objects not yet produced by the construction contractor, as in one of the studied cases as shown in the middle of Figure 4, where sheet metal sleepers on the floor show where a future wall would be built.

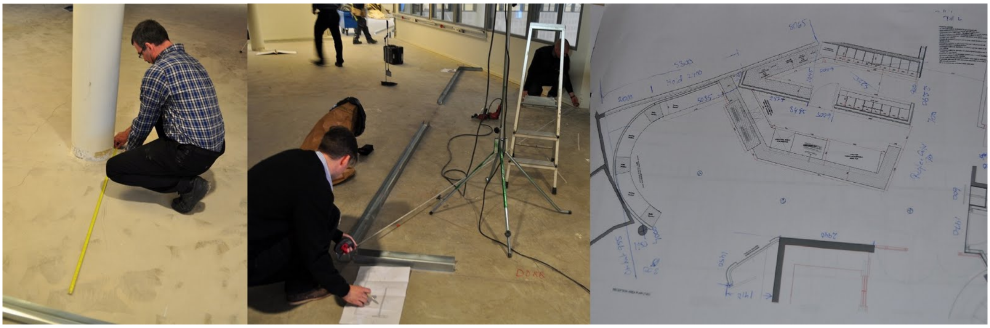

Figure 4: Current measuring methods. From left: manual tape measuring, diagonal measuring on walls not yet present, insertion of measurement data on paper drawings for transfer to production pre-processing.

The time required to perform the measurements varies from a few hours to hundreds of hours, and is difficult to estimate from the prescribing documents when making the quote. For the annual sales volume of €50 million, about 1700–2000 hours are used for geometric measuring before production, which would represent about 0.2–0.4% of the turnover in direct costs. Although this is the true cost, the impacts of problems related to the geometric verification are believed to be significant; for example, the studied cases have shown that 3D anomalies (e.g. floor–wall angles other than 90°) were not revealed by the manual (2D) measurements, and therefore the degree of prefabrication is limited and problems were left to be solved when assembling the joinery products on-site which increased the uncertainty and time to perform the assembly on-site.

Pre-processing and Manufacturing

When the order is received the work of defining a product from the information given, developing production methods, scheduling the production start, ordering production supplies, and planning outgoing deliveries. This work is done in the production pre-processing. For this work, information is required from different stakeholders. For example there is prescribing information from architects, contract information from sales and the contractor who is the usual client of the joinery-products supplier, coordination information from the contractor and assembly subcontractor, and results from the on-site surveying. This information is processed into work orders for the production machines and personnel. The main information carriers to the manufacturing are 2D drawings, manufacturing bills, and a production plan.

The manufacturing of the products is performed using information from pre-processing. This information is communicated mainly by 2D drawings and a manufacturing bill. A production plan is used to show the manufacturing time requirements. Before transport, groups of product components are put together in parcels. The transport to the construction site is performed by a forwarding agent.

Observations in the off-site production

The production units studied were companies with less than 20 employees. Much of the defining work was performed by a single person in production pre-processing in these companies and was a role with periods of high workload. The main support for this work was CAD software and the companies' own routines developed for created manufacturing bills and production plans for the production staff. The small size and slim organisation of the production units and high workload of key personnel have shown that limited resources are used in developing the work according to new theories and technologies. Further there were limited quality control of the pre-processing, and logical errors were seen to pass down the value stream and were not revealed until the on-site assembly. Examples of this can be seen in Figure 6.

Assembly-planning and on-site assembly

The planning of the assembly is performed concurrently with the production stream. Since projects are geographically spread out, the strategy applied is to contract assembly contractors close to the construction site. The main tasks of the assembly planning are contract assembly and coordination with the production. The assembly of joinery products is work that is usually done under the pressure of time. Finishing the assembly late generally affects the constructor's ability to hand over the project to the client in time. An early start would be desirable but then the supplier contract closures are generally close to the minimum lead time stipulated by the supplier. Thus it remains to improve the efficiency of the assembly work.

The product assembly is performed on the construction site. The main information carriers are 2D drawings from the architect, and occasionally some sketches from the pre-processing. Assembly instructions or exploded views are usually not supplied to the assembly contractor. Often the assembly contractor needs to communicate with the production pre-processing in order to develop an understanding of how to assemble the product. If the assembly is contracted close to the time of receiving the product order, the method of assembly may be developed in collaboration with the assembly contractor. Normally the assembly work needs a large proportion of ad-hoc problem solving and on-site coordination with other contractors. The logistics from manufacturing to assembly are not a controlled activity in this supply chain and performed by an external forwarding agent.

Observations of on-site receipt of deliveries

From the production units the components of the joinery products were parcelled prior to transport to the construction site. The making of parcels was done at the factory, focusing mainly on establishing sturdy parcels. The production units claim that the parcels have labels declaring the content but observations show that the level and existence of this labelling varies, which complicates the understanding of the delivered components for the assembly and slowdown the pace of assembly. Parcels are transported from the producer by an external dispatcher. The arrivals of deliveries were not coordinated with the assembly needs but rather with the time of manufacturing and therefore storage of components on-site were needed when waiting to be assembled.

Figure 5 shows the activities involved in receiving parcels on-site. The examples show a considerable amount of waste, supply chain disintegration, and lack of coordination. Here more time and resources were used than are needed in a well-planned delivery. Lack of scheduling precision caused unnecessary resource allocation when extra staff was allocated one day when the delivery did not arrive. Further determining how to transport incoming parcels into the building was not performed in advance due to absence of delivery planning. Therefore the parcel design gave no consideration to spatial constraints in on-site transport routes, and so the parcels needed to be disassembled to fit the freight elevator. Except making the delivery receipt more time and resource consuming this procedure exposed the joinery components to risk of damage and if damaged, the goods must be repaired or replaced. The necessary lead time for replacing damaged goods could delay the finishing of the assembly and consequently also the construction project, which would lead to penalty claims from the construction contractor.

Figure 5: On-site receipt of ETO joinery-product components.
From left: two people are checking possible transport routes, three people are waiting for a tractor, two are disassembling parcels, and two are trying to fit components into the freight elevator.

Observations on assembly information

When performing assembly on-site the assembly contractor needs information to understand how to accomplish the assembly. The main information carriers were 2D drawings on paper from the architect and complemented by some additional sketches from the production pre-processing. As the information from production pre-processing was adjusted according to the geometrical measurements of the environment this information did differ from the drawings of the architect. Thus the pieces of information provided did conflict with each other. Observations showed that differences between architectural drawings and sketches from pre-processing were not easily detected. The low level of information generated a need to establish direct communication with the production pre-processing. Observations showed on several occasions that when an assembly contractor needed to communicate the production pre-processing staff were not available. It was obvious that the need for direct communication interrupts the flow of assembly as well as production pre-processing. The assembly contractor highlighted the need for information that would be easier to interpret, like 3D views.

Assembly problems

When the assembly started, the date when the work was supposed to be complete was known. More detailed scheduling was lacking; for example there was no exact resource allocation or time schedule on component-, hourly, or even daily level. The detailed production design of the assembly work was performed by the assembly staff in cooperation with production pre-processing. In the observed cases this was part of the assembly work and started when the components of the joinery products arrive at the construction site. The assembly planning shown in the value stream map focused mainly on contracting an assembly contractor to the supplier project and coordinating the start with the manufacturer's ability to deliver the components to the construction site.

When supplying a joinery product, the design of the product, production, and assembly needs to be done in every specific project. Under the pressure of providing short lead time, a solution is delivered, regardless of whether it is the optimal solution in every aspect. Observations reveal that this caused efficiency losses in the assembly. Figure 6 show some aspects of this. First, the product design (shelving base) leaved more work for the assembly to manage than was necessary. Another design could have reduced the time spent on this operation significantly. The next two parts of Figure 6 show a logical error in the production pre-processing that passed through production and ending up at assembly to be solved. This added work to assembly that should not be needed. The final picture in Figure 6 shows lack of coordination of adjacent processes. Cast in anchor points are made in a concrete stair by the constructor. However, they are not positioned to fit the design of the joinery stair railing already prescribed by the architect. The consequence is a significant increase in assembly time.

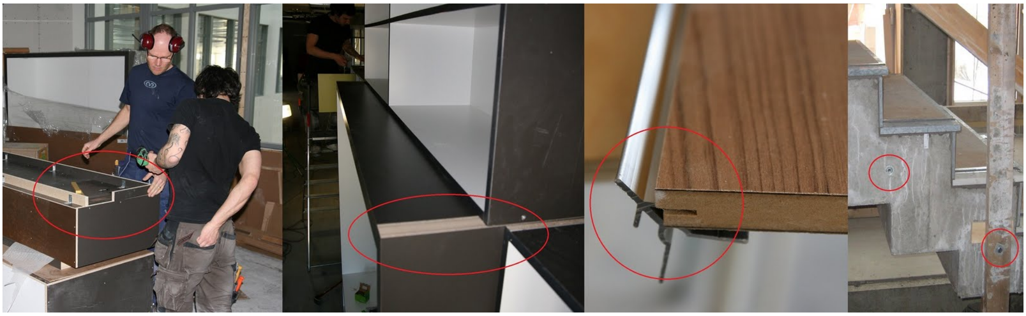

Figure 6: Example of problems in assembly. From left: the shelving base needs to be redesigned, laminate is missing on the lower shelf, two components do not fit together, and finally cast in anchor points have been misplaced.

The carrying out of the assembly on-site involved coordination with other contractors on-site. It was noticeable that the performance of much of this coordination was left to the assembly staff. This was a significant part of the assembly work studied. Coordination often generated changes in which work should be in hand. Many of the problems shown were not normally detected and treated as problems in the quality reporting. The quality systems used were not designed to handle these types of efficiency restraints. Therefore limited organisational learning from assembly problems took place in the studied joinery-products supply chain.

Discussion

As the main objective in this paper is to define the main contributors to inefficiency and to define areas for innovation, considering this objective the lean methodology is used to define wastes occurring and their root causes. From the case studies it is evident that waste is present in the process of supplying joinery products to construction. Increased knowledge about waste occurring in this area of the construction industry is essential to improve the performance of the supply process. The causes of detected waste are analysed according to the principles of Lean and information management. By using a Lean perspective the ability to see problems emerged. The problems encountered late in the supplier process, for example in assembly, are seen as symptoms whose root causes are likely to be traceable upstream.

Main contributors to inefficiency

In supplying joinery products, much information needs to be managed: in relation to the case studies, this includes information about the design, producer planning, on-site production planning, production methods, resource allocation, sub-contractor coordination, and so on. In the cases studied much attention is given to the business transaction and the design information. Planning, coordination, and assembly information is given little attention, leading to the problems observed.

Due to inadequate precision in construction tolerances, spatial as-built information from the construction site is required. This generates multiple types of waste, for example in transport, over-processing, and defects. Currently used methods for retrieving spatial as-built information are insufficient to increase the level of prefabrication of the joinery products. The amount of information and level of precision offered by current methods are simply inadequate. Therefore assembly needs to use craftsmanship methods to manage spatial uncertainties, which increases the time required for on-site work. In production, elimination of the spatial uncertainties would also benefit efficiency when only the required parts of the components have to be produced.

From the cases studied it can be seen that vertical supply chain integration is essential in establishing higher levels of prefabrication of joinery products. It is necessary to approach efficiency improvements through an increased level of concurrent engineering changes in the procurement relation. This might be outside the control of the joinery-products supplier since major construction contractors possess more power in the negotiations. However there is still the potential for vertical integration of the supplier's own supply chain. Assembly efficiency is an area that the joinery-product suppliers should be able to approach by themselves. There are three major contributors to assembly inefficiency found in the cases studied:

- Inadequate planning and coordination
- Absence or inadequacy of assembly information
- Spatial uncertainties

All three relate to sharing, exchange, and modelling of information. From a Lean perspective, process flow is central. Tact and just-in-time (JIT) concepts are essential in establishing flow, which requires planning and coordination when working in a cross-organisational manner. The case examples show severe limitations in planning and coordination, which, according to Tommelein *et al*. (1999), lead to work flow uncertainty and thus loss of work efficiency. Especially in assembly, efficiency should improve with increased use of planning and coordination tools and philosophies. Adjacent processes and sub-contractors should also be considered in the planning and coordination activities. This is information that can be modelled, making it more visual and easier to survey. Adoption of the principles of the Last Planner system (Ballard, 1994), integrated project delivery (Anon., 2007), and Line of Balance and 4D/nD information modelling (Björnfot and Jongeling, 2007) seem to be potential innovations for this area of problems.

Absence or inadequacy of assembly information disturbs the flow and process efficiency. It would be possible to achieve increased efficiency in the assembly knowledge build-up through efforts in the 3D modelling of the joinery products. In the cases studied the construction projects have been using 2D CAD modelling. Therefore to perform 3D CAD modelling the joinery-products supplier needs to create the models instead of re-using 3D CAD models performed upstream, which decreases the motivation for the joinery-products supplier to perform 3D CAD and hampers efficient use of the on-site 3D information for creating joinery products with appropriate spatial fit. Despite this fact, there is much to suggest that increased 3D modelling by the joinery-products supplier would generate increased possibilities in improving assembly information with limited extra effort (Jongeling, 2008). Making the information easily understandable and usable in the assembly situation is an important issue in improving assembly performance.

Waste occurring

The following model present the actual wastes found in a Lean perspective as a result of the main contributors to inefficiency. In other words the root causes for the following wastes are found in the main contributors to inefficiency. In the analyse we find that over-production does not apply well to the ETO production studied. The findings relate more to under-processing, causing waste downstream, in the cases studied. We define under-processing as deficiencies in information and materials forwarded through the value stream causing inefficiency in downstream processes. In the model used here over-production is therefore replaced with under-processing, and thus the acronym TIMWOUD is used in the presentation of wastes in Table 1:

Table 1: Identified TIMWOUD waste

Unnecessary **Transport** is found in: - The need for a skilled measurement performer to visit each project location - The need for complementary measurements on different occasions - Logistic solutions, causing extra transport to be used before products are sent to the construction site - Relocation of assembled components due to insufficient coordination of contractors on-site - Ill-fitting components, requiring transport to workstations for adjustments - Transport of replacement products
Unnecessary **Inventory** is found in: - Design documents waiting to be processed prior to production - Parcels waiting at the forwarding hub before being sent to the construction site - Products and components arriving at the construction site before they are needed by assembly - Knowledge gathered early in the project not being communicated downstream in an effective manner
Unnecessary **Motion** is found in: - Parcels needing to be unpacked before entering the construction site in order to fit the transport route, which multiplies the number of unloading motions (Figure 5) - Insufficient coordination with other contractors, increasing the number of assembly contractor motions
Unnecessary **Waiting** is found in: - Contracted delivery receivers waiting one day for deliveries which do not arrive - Assembly work being put on hold due to absence of information - Assembly work being put on hold due to the need for other contractors to perform work
Over-processing is found in: - Business transactions that take more calendar time than that spent realising the joinery products - Business transactions that are performed on project level - Processing of material that will be cut away in assembly due to spatial uncertainties - Adjustments of components due to logical errors and spatial uncertainties (Figure 6) - Assembly rework due to insufficient coordination of contractors on-site
Under-processing is found in: - Business transactions, when all information needed for supplying the product is not communicated - Component definition when products cannot be fully defined due to spatial uncertainties

- Product definition when logical errors pass downstream - Communication of insufficient information, leading to a requirement for interaction with pre-processing - Planning of assembly work: absence of details, only start and finish times are given, no tact - Coordination of assembly work with other contractors on-site - Manufactured material that needs to be cut away at assembly due to spatial uncertainties
Defects are found in: - Faulty drawings and sketches used by assembly - Drawings that hold information details that are too small to read at assembly (Figure 6) - Not all of the necessary information being correct or present due to spatial uncertainties - Spatial information: not all of the necessary measurements are present or correct - Parcel labelling: not all components are labelled, obstructing assembly efficiency - Faulty components, due to uncertainties in the spatial measuring and logical errors in production pre-processing - Assembly work, due to absence of information, causing rework

Areas for innovation

In Figure 7 a generalisation of the observed problems of the seven wastes of Lean is developed, illustrating the efficiency potential of eliminating waste.

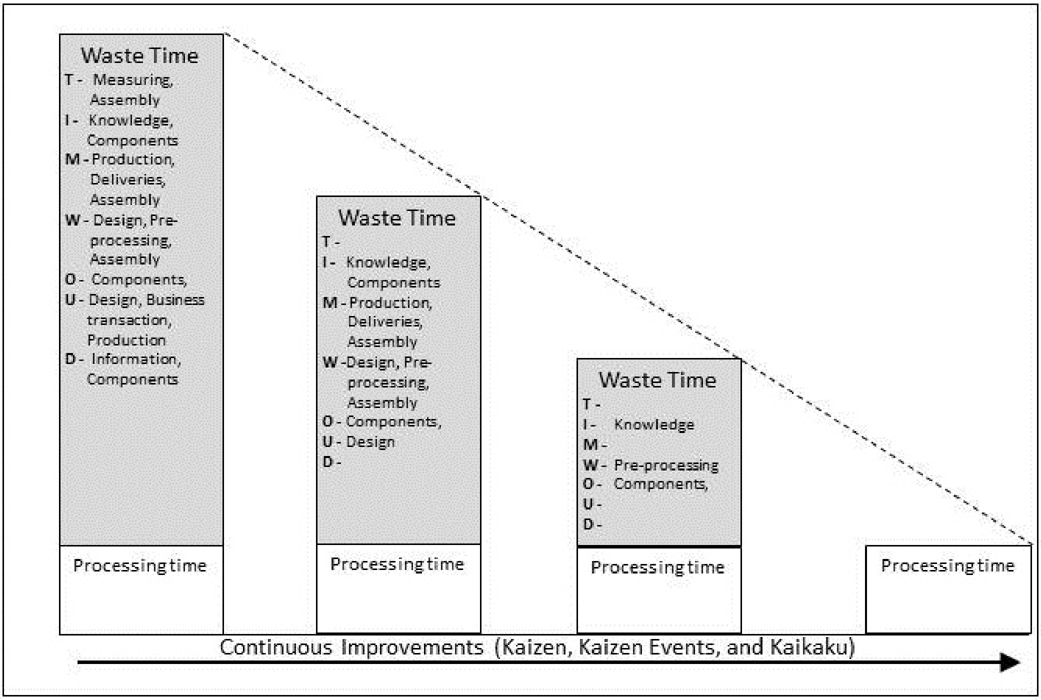

Figure 7: Waste elimination as a means of improving process efficiency (after Koskela, 1992).

The presence of waste in each part of the TIMWOUD acronym has causes at different organisational levels and cannot be eliminated "letter-by-letter" without extensive organisational efforts. However, it is important to find the root cause of the problems at a cross-organisational level in order to avoid sub-optimisation. When dealing with root cause problems, Lean principles could be used for guidance. In the cases studied, violation of Lean principles like the management principles of Liker (2004) can be found. Below, the cases are analysed with respect to the four areas of Liker's management principles.

Long term philosophy
In construction the culture is to run projects using temporary organisations. This is strongly reflected in the contractual relations. The culture in construction is likely to affect the culture among the suppliers as well, which is seen in the cases studied. What is seen is that the progress of each project always has the highest priority. Despite high variability in resource use for similar projects, little long-term development is used over the supplier supply chain. A strategy to approach major customers to create long-term agreements with mutual incentives for increased efficiency in the process would be desirable. More focus could be placed on developing an efficient process instead of working with the business transaction for every single project. Such types of agreements should also be reflected in the supplier supply chain; for example, supplier and assembly contractors' relations could be developed with a long-term philosophy in mind.

The right process will produce the right results
A difficulty in supplying ETO products is that part of the contract is to find a suitable process for the specific product. With a limited product value, it was seen that only minor resources were used for developing the process. Further, each node in the supply chain has little cooperative development of the overall process. More development of standard procedures and types of solutions at a modular level would be desirable. If the supplier extends its ownership of the total process and educates assembly contractors that it works with, increased project efficiency could be achieved. Further the workload of some resources shows variability and flow disturbances. Methods for workload levelling would be possible with increased knowledge of the overall supply chain process.

Add value to your organisation by developing your people and partners
The joinery-products production companies studied work together under a common brand used for the sale of their products. The sales are done by a co-owned sales company. According to the European classification, the organisational structure of the majority of joinery-product suppliers operating on the Swedish market is small- and micro-sized companies. None of the production companies studied have more than twenty employees and the educational level is generally rather low, which can be a potential restraint for innovation in using new technology. The concept of working in a network can be generalised by any small joinery-products suppliers. Then research and development issues could be approached with joint forces, not just by the sales department as in the current situation. An approach to integrate the supplier's supply chain as well as integrating efforts towards the major customers would be desirable. With increased focus on the process and supply chain, stakeholders in those processes should be able to decrease and even eliminate waste in the overall process. For example, in one of the cases studied, the assembly contractor was not aware of the quality procedures stipulated by the joinery-products supplier. Therefore assembly time had to be used to study the stipulated quality handbook.

Continuously solving root problems drives organisational learning

With increased focus on the supply chain process, increased knowledge about the presence of waste found in the cases studied could be achieved. Currently there is a culture through the supply chain of solving problems as they emerge. With this culture, problems are not detected and thus the root cause is not analysed. Therefore limited organisational and inter-organisational learning takes place through the value stream and problems reoccur repeatedly.

An important measure to eliminate waste lies in the information management. Management of information in the cases studied needs the involvement of inter-organisational functions, cooperation, and knowledge build-up through the value stream. To enhance knowledge creation and build-up through the value stream, information needs to be accurate, achievable, accessible, and understandable for all stakeholders, which was not observed in the cases studied.

As the product in the upstream process is purely information-based, management of the knowledge build-up is essential in developing process efficiency. Figure 8 illustrates the current knowledge build-up and communication of information through the value stream. What is seen is that this is a sequential process and that the information medium does not efficiently transfer knowledge in such a way that the next downstream process can add directly to the accumulated knowledge. Ideally the process should be more concurrent and interactive and information should be communicated efficiently through the value stream without any knowledge drop occurring in each downstream handover.

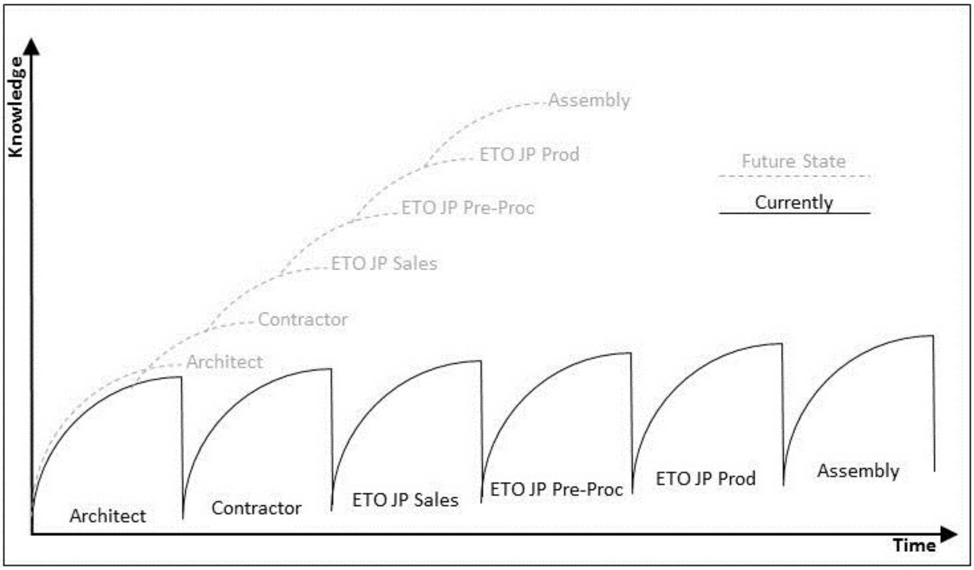

Figure 8: Potential of concurrent engineering approach

From an efficiency perspective, the current method of procurement leads to over-processing of the business transaction for the joinery-products supplier when working on project level. This obviates major gain in applying concurrent engineering methods to the value stream. In the studied cases production pre-processing is central; it is where the architectural ideas are formulated into products and where ideas about assembly methods are created. Long-term procurement relations would enhance integration and information exchange between the architect, pre-processing, and assembly in the product determination, as observed in Bystedt (2007); for example, the supplier product competence can be useful in the architectural determination that can enhance product quality and process efficiency. Further, the supplier workload variability can be reduced and process quality can be enhanced. Technology such as parametric 3D CAD models would be desirable information carriers in this interactive information exchange. To make efficient use of the time on-site, coordination with the construction contractor and sub-contractors carrying out processes adjacent to the joinery-products supplier is needed.

Current practice in construction generates a need for joinery-product suppliers (and other suppliers and sub-contractors) to verify spatial as-built information since general tolerances in construction do not provide enough precision. The observations made during the case studies, and also the common experiences of the joinery-product suppliers of the case studies, show that deviation of the spatial as-built information from architectural drawings is common and in many cases larger than stipulated tolerances (Anon., 2008).

Despite the efforts of joinery-products suppliers to verify spatial as-built information, their methods cannot eliminate the spatial uncertainties. These uncertainties decrease efficiency in both production and assembly. Methods and technology for eliminating spatial uncertainty would be of interest for this type of industry to help eliminate many current process deficiencies such as defects, over-processing, and over-production in production and assembly. Different 3D scanning technologies seem interesting but questions remain about the performance they can provide and whether they can be cost effective. When to perform measuring and refine information into CAD models is also an intricate question. The product engineering and realisation require a certain lead time. Before starting production the joinery-products supplier need spatial as-built information, but often the product environment is not ready for measuring the as-built environment. Proposed changes in procurement and more efficient information management could decrease the production and assembly lead time and therefore decrease the problem of when to measure the as-built environment.

Conclusions

From the evidence provided in this article a vast amount of waste is present in supplying joinery products to construction from a Lean perspective. Innovation in adopting Lean principles and management of information, supply chain, planning, and coordination is believed to be essential for improving total process performance in this area in construction.

Main inefficiency contributors

Much of the information communication problems observed are those that arise from the suppliers' own processes and then surface during assembly. Approaching assembly inefficiency problems is something that is within the power of the joinery-product suppliers to change. Three major contributors to assembly inefficiency were found in the studied cases:

- Inadequate planning and coordination
- Absence or inadequacy of assembly information
- Spatial uncertainties

For the joinery-product suppliers there is a need to verify spatial as-built information since general tolerances in construction do not provide enough precision. Despite current efforts to verify spatial as-built information, their methods cannot eliminate the spatial uncertainties and they need to work with methods to handle spatial uncertainty, which decreases efficiency in production as well as in assembly. Cost effective methods and technology for eliminating spatial uncertainty are highly interesting for this type of industry. These main contributors for inefficiency in assembly are seen as the root cause for the findings of waste in; Transport, Inventory, Motion, Waiting, Over- and Under-processing and Defects.

Areas for innovation

Generally in construction, attempts at increased levels of industrialisation are approached through increasing the level of prefabrication, for example in industrialised housing (Lessing *et al*., 2005). Thus efforts are made to move construction activities from on-site to off-site since this is believed to increase the predictability of the work on-site (Howell, 1999). This is parallel to the findings presented in this article. An increased level of prefabrication of joinery products, decreased assembly time, and increased predictability of on-site work seem possible. The cases studied provide information about four main areas of improvements:

- Long term philosophy
- Standardisations in process and communication
- Development of individuals and partners
- Continuity in solving root problems

A procurement model based on a more long-term relation than project level would be desirable. Then over-processing in the business transaction could be avoided as an advantage of more concurrent and interactive work between those who create value, in these cases the architect, pre-processing, production, and assembly. This would provide more efficient knowledge accumulation through the value stream since information would be shared and mutually developed.

To adopt the principles of Lean, more focus on flow is necessary, and thus an increased level of planning and coordination is required, according to Tommelein *et al*. (1999). Currently little coordination between on-site sub-contractors and assembly is performed in advance, which has a major impact on efficiency. Performing assembly of one-of-a-kind joinery products with or without limited assembly information disturbs the work flow and process efficiency severely. Increased efforts of the joinery-product suppliers in 3D modelling and generation of exploded views are likely to enhance assembly efficiency. Further use of information technology tools for increased visualisation and efficient knowledge transfer is also believed to be useful in this context.

The identification of waste and their root causes in supplying joinery products to construction is a start for future work on improving this area of construction. These case studies cannot provide the complete picture of the general situation of supplying ETO joinery products to construction. However, together with more research in this area they can contribute to the theoretical generalisation. More research on adopting Lean principles and management of information, supply chain, planning, and coordination in this context is needed. In the cases studied the procurement model and information communication inefficiency are the main hindrances. How to find solutions to those problems is not clear and prerequisites for performing suggested methods and their efficiency in this context need to be proven.

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Paper III

3-D As-Built Spatial Verification in Supplying Engineer-to-Order Joinery Products to Construction

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3D As-Built Spatial Verification in Supplying Engineer-to-Order Joinery Products to Construction

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ABSTRACT:
Supplying engineer-to-order joinery products to construction involves highly refined one-of-a-kind products engineered to fit specific requirements. Before starting production and planning the assembly, the supplier needs to verify the as-built dimensions on the construction site. Manual methods of verification in use today introduce uncertainties and do not provide joinery-product suppliers with enough information to plan, produce and assemble the products efficiently. Because of dimensional uncertainties in the installation site, joinery products are designed to be altered during on-site assembly. A model created from coordinate-measuring-machine data and point-cloud data was compared with the model created and used by the joinery-products supplier for production . Comparisons show that the basis for production used currently suffers from dimensional uncertainties that have to be dealt with during on-site assembly. By using 3D surveying methods, the dimensional quality should be increased, and the 3D information would allow the joinery-products supplier to deal with the dimensional uncertainties in a computer environment instead of on the construction site. The increased quality of the dimensional verification should result in better-fitting products and thus fewer man-hours spent on the on-site assembly.

1. Introduction

When supplying construction with Engineer-to-Order joinery products, the joinery-product supplier must verify the spatial dimensions of the construction site before manufacturing the products. Today, joinery-product supplier base their designs on architectural drawings, which do not reflect the as-built dimensions. In an attempt to correct this, on-site dimensional verification is performed to verify and revise the architectural drawings with as-built measurements before starting production. Forsman *et al*. [1] studied the process of supplying joinery products to construction from a lean perspective and found that much waste is present in the process. One of several areas in need of improvement is dimensional verification. Verification is often conducted manually with folding rulers, tape measures, *etc*. and is done in 2D. The spatial data achieved is sparse and unreliable and the lack of 3D spatial information is a weak basis for production of the joinery products, which means that products often must be adjusted during on-site assembly to assure a good fit. It also means that joinery-products are designed to be altered during on-site assembly. Manual measurement is time consuming, labour intensive, expensive and unreliable [2, 3]. Despite the suppliers' efforts to verify spatial as-built information, their manual measuring methods cannot eliminate spatial uncertainties, which decrease efficiency in production as well as during on-site assembly [1]. Given that the machines used by the joinery-products supplier can produce with tolerances down to tenths of a millimetre, the level of prefabrication could be increased through a more accurate description of the installation environment. The increased quality of the product would lead to more focus on the assembly rather than on adjusting the products during installation.

The joinery products are produced off-site because of benefits such as, better work environment, easier to access work, less damage, *etc*. [4]. Off-site production is dependent on accurate dimensional information from the construction site. If there are errors in the dimensions captured on the site, the product must be produced to be altered or, in worst case, reproduced. To fully reap the benefits of prefabrication, the integration of prefabricated products requires higher precision of on-site environment measurements [5]. Arayici and Hamilton [6] stress the importance of digitizing the as-built dimensions of constructions, since drawings are inaccurate or might be missing when refurbishing buildings. 3D digitizing equipment, such as laser scanners and coordinate-measurement machines (CMM), could be used to acquire more accurate dimensional data.

During the last decade, laser scanning has gained attention within areas such as quality control during construction [7], surface reconstruction of complex structures [8, 9], reconstruction of as-built building information models [10], 3D visualization of construction site for construction planning [11] and as-built deviations through comparison of 3D scans and planned-build CAD drawings [12]. The focus in these cases has been on visualization and on surface and model building. Little, or no, effort has been devoted to dimensional verification. CMMs have been used for reverse engineering of products; however, most CMMs used are stationary and not possible to use for digitizing construction sites. Prodim [13] developed a mobile CMM with the measuring probe attached to a wire for digitizing ship interiors, and this is suitable for digitizing larger objects.

Recreating buildings with 3D technology is analogous to reverse engineering. The reverse-engineered on-site environment would give the production preprocessor accurate 3D spatial information on the site and provide the possibility to perform quality control of the on-site geometry. By dealing with the uncertainties in a controlled computer environment during design of the components, instead of during the on-site assembly, the quality of the process could be increased [T.-Y. Hsieh]. This would lead to a decrease in the man-hours spent on on-site assembly by focusing the on-site work on assembly and not on alterations of the joinery products' component. The joinery-products supplier could have access to all geometry and can make all necessary changes so that the product will fit well into the installation environment before production starts. The gains from saving man-hours not only decrease cost for a single project, but also create time for completion of more projects annually.

As a part of enhancing the process of supplying joinery products to construction, the potential of decreasing dimensional uncertainties for joinery-products suppliers has been explored. The main idea of this paper is to introduce and discuss 3D measurement techniques that can be used to reverse-engineer the installation environment in order to achieve more qualitative dimensional data. The increased quality of the dimensional data should decrease several of today's uncertainties and enhance the production process. The products can be designed to a higher quality and better fit than with current methods, and this will, in the end, reduce the man-hours spent during installation, and thus the cost of this process, and also reduce the time required for each project.

2. Method

2.1 Prerequisites for the study

This research has been conducted through a case study where a joinery-product supplier were followed when surveying a construction site for dimensional verification. The verification of the dimension is used as basis for their production. The joinery-products that were supplied in this case were all highly refined one of a kind Engineer-to-order joinery products.The parts of the construction site that were surveyed consists of a large open area, the reception and visitors area, and a long narrow room, the cloak room, approximately 100 square meters in total (Figure 1). In the reception area the supplier provided a sofa and a reception desk and for the cloakroom a floor to ceiling shelving system. All the interior design of wall panels was also delivered by the joinery-products supplier. At the time of surveying, the site was under reconstruction and the on-site environment consisted mainly of gypsum boards, glass areas and concrete floor.

2.2 Observations of the current surveying process

The current used methods in acquiring spatial information of the installation environment for the joinery products before manufacturing was examined. The data was collected through interviews and observations when performing the surveying and when processing the information into work orders to the manufacturing. The data were documented through voice recordings, notes, and photographs. Special attention was given what information the surveyors captured and how this was documented and distributed to those concerned. Further the on-site assembly of the joinery-products were studied with the purpose to identify how the acquired spatial information affects the performance of the assembly work.

2.3 3D measurements

In connection with documenting the joinery-products supplier’s work, two different 3D measuring techniques were used to capture the geometry of the on-site environment. The equipment used was a Prodim Proliner 8 coordinate measuring machine [13] and a Leica Scan station C10 long-range laser scanner [15]. The joinery-products supplier’s model, which is based on the 2-D data from their dimensional verification of the site, was compared with the results from the 3D measurements. The raw data from the CMM were refined into a 3D CAD model in Siemens NX 8 [16]. Processing of laser scan data was done in Siemens Imageware 13.0 software [16]. The models and point-cloud were super positioned in Imageware and the geometries were compared to evaluate whether the 3D techniques can depict the on-site environment better than 2-D techniques.

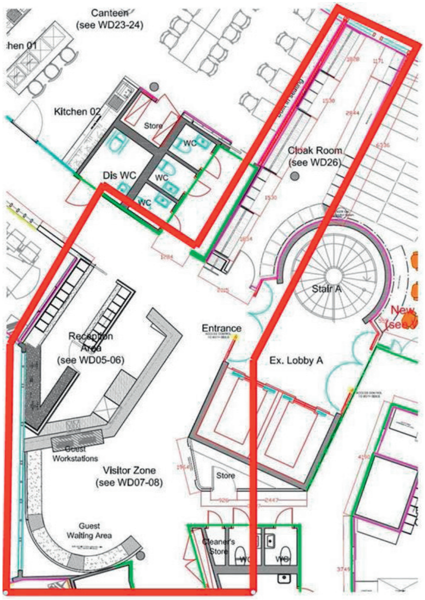

Figure 1. Architectural drawing of the reception and cloakroom area.

2.3.1 CMM measurements

The Prodim CMM consists of a stylus measurement probe connected by a 7.5-meter-long wire to the main unit. Measurement accuracy according to the manufacturer is 0.4–0.7 millimeters over 2–5 meters. Single point accuracy was tested and ranged from 0.27–0.36 millimeters at one meter to 0.79–1.13 millimeters at a distance of 6.5 meters. When measuring with the Proliner, the surveyor needs to plan the survey and must decide where to start and stop since the equipment requires that the surveying is performed either counter- or clockwise to use the automatic off-set functionality. The density of the measurements is decided by the surveyor. Each coordinate is manually acquired, and the distance between the acquired coordinates determines the density of the 3D spatial information. For a good depiction of the curvature of a wall, the density of the captured coordinates must be greater than, for example, for a flat glass surface. The geometry generated by the CMM consists of lines and curves.

On-site measurements with the CMM were carried out acquiring coordinate by coordinate and, for curved areas, by sweeping the stylus probe over the surface. The surveyed area required the CMM to be moved in order to measure all required surfaces. When moving the CMM during surveying, the unit had to be calibrated against four markers, moved and calibrated again. The movement of the CMM introduced a measurement error of 1.66 millimeters. In order to completely capture the on-site environment, the unit had to be moved three times. The data captured with the CMM were imported into and processed with Siemens NX 8 CAD software to create 3D models. Walls and planes were extruded from the captured curves. The time spent for surveying with CMM was approximately one hour.

2.3.2 Laser scanning measurements

The laser scanner uses time of flight to calculate the distance to the object. A laser pulse is sent out and then reflected from the target. With the speed of light being a known constant, the distance can be calculated. The accuracy of a single measurement of the laser scanner is, according to the manufacturer, six millimeters in position (x, y) and four millimeters in distance (z) at 1–50 meters [14]. The noise depth in the point-cloud is measured to 4 millimeters. When laser scanning, each captured point is represented as a coordinate, and the cluster of coordinates is referred to as a point-cloud. During the scan, the surveyor needs to plan the survey by placing targets, spheres in this case, in line of sight in order to merge the different sub clouds into one. The scan itself is conducted automatically. During scanning, a coordinate was captured for every 60 micro radians. The scanner was moved three times in the surveyed area in order to measure all required surfaces. The four clouds were merged into one cloud by the surveyor (Figure 4). There is no need for calibration between the scans, as the software uses the spheres to triangulate and merge each scan position. The error introduced between the movements is 1–2 millimeters. The laser scan was carried out by Mättjänst AB and took approximately 45 minutes.

3. Results and discussion

3.1 Current surveying process

The production preprocessor of the joinery-products supplier defines the product from the dimensional verification of the construction site and prescribing documents from architects. The information is used to develop production methods, scheduling the production start, ordering production supplies and planning outgoing deliveries. It was observed that the production preprocessor initially used an architect’s drawing to define the measurements needed for as-built dimensional verification. In the architectural drawing, important measures for production pre-processing were predetermined. Before the dimensional verification can even start, the production preprocessor has to define which dimensions to capture. From the predetermined list of measures, the surveyor worked to capture wall placements, diagonals in the rooms, pillar placement and doorway placements. Measurements were taken with tape measures and folding rulers (Figure 3) and noted on printouts of the architectural drawings (Figure 2).The manual survey was conducted during half a day by two persons. The time for the manual measurements was not coordinated with the construction project, and therefore not all spatial information was possible to retrieve; *for example,* a wall in the reception area had not yet been built. Sheet-metal sleepers for the wall were mounted on the floor and used to determine the wall position, but actual measurements of the wall location were not possible to capture at the time.

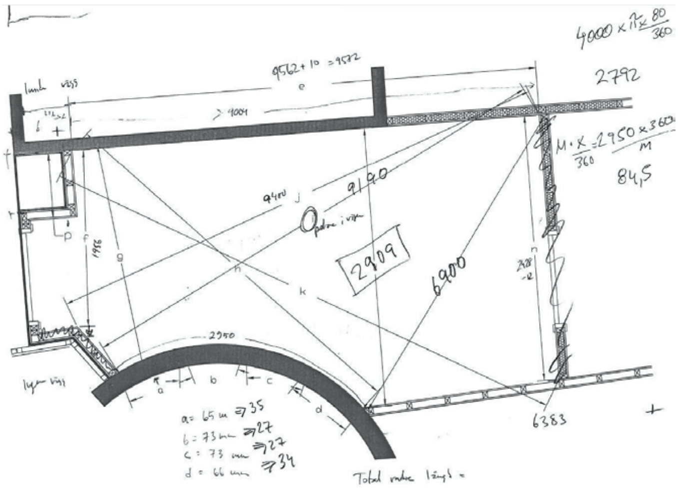

Figure 2. Paper drawing of the Cloakroom (not to scale). Manual measurements have been made by the supplier and inserted manually in this printout.

3.2 Consequences of the current process

To summarize the observations of the manual measurement performed by the joinery-products supplier, it can be seen that the manual method is error prone, time consuming and results in dimensional uncertainties. The measurements that were defined by the surveyors were all made at floor level, which means that the data are limited to a 2-D representation of the site. By excluding the third dimension, no concern is taken to angles between walls and floor or wall planarity, *etc*. One of the consequences of this procedure is that the production preprocessor has to use time to define the measures that he views as important before the surveying can start. Furthermore, it was found that not all necessary measurements were acquired, which led to another day of dimensional verification. The construction site was situated a one hour airplane flight away from the surveyor, resulting in unnecessary travel time and the loss of man-hours.

The inadequate dimensional verification causes delays both in the production and in the assembly work at the construction site. Lengthy delays can, in the worst case, make the project time exceed its due date and can result in fines for the joinery-products supplier. The dimensional verification is the basis for producing components of the joinery products. Because of the sparse and erroneous information, the products are designed to be altered to fit during assembly. This implies that the assembly personnel have to work more as carpenters than as installers, which requires craftsmanship skills. Not only do the products require alterations, but, in the worst case, the dimensional basis for production could be so deficient that it might lead to products having to be reproduced. If the supplier has to reproduce joinery products, it will delay the assembly work and restrain production capacity.

Difficulties during measuring were observed when the personnel were trying to reach corners and other nooks with tape measures. The actual reading of dimensions is prone to introduce errors from rounding off; for example, when they were trying to measure the center position of a pillar (Figure 3). The positioning and reading of the tape measure, especially in tight corners, also contributes to the error in manual measurement. Measuring radii with tape measures and folding rulers is difficult and time consuming. Templates are created and used for verification. A 10-meter-long tape measure has a precision of +/- 1.1–2.3 millimeters [17] and an accuracy uncertainty of +/- 0.5 millimeters[18]. Measurements were communicated by handwritten notes on drawing printouts, which increases the risk for misinterpretation of measurements (Figure 2). All these errors contribute to the uncertainties that are found in their dimensional verification.

The low quality of the acquired dimensional data is derived from human errors such as rounding off, reading errors and communication of measurements through handwritten notes. Another contributor to the low quality is the fact that the measurements are all done at floor level, giving only a 2-D depiction of the on-site environment. Measurement of radii is difficult to perform with the current method; often, cardboard templates have to be used. Because of the 2-D depiction of the on-site environment, it is not possible to adjust the joinery products in the computer; instead, they are produced to be altered on site. The gathered spatial data are very sparse, and the low level of known dimensions results in products that have to be altered during on-site assembly. Acquiring as-built dimensions requires that all the prerequisite building work has been completed and coordinated with the building contractor.

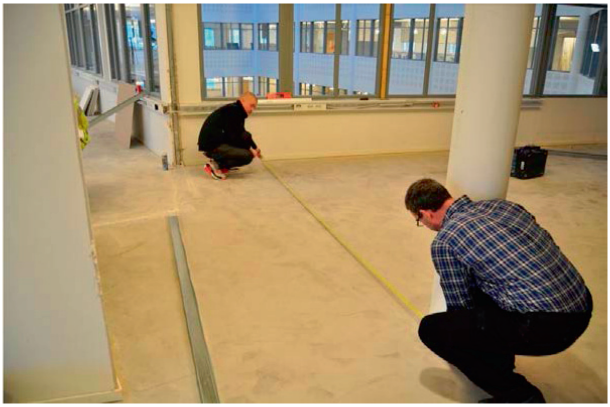

Figure 3. The image shows how the length from the wall to the center of the pillar is measured.

3.3 Comparisons of 3D data

The captured spatial information from the CMM and laser scan is shown in Figure 4A. The CMM data are the basis for creation of the 3D model. It can be seen that there is big difference in the number of captured coordinates. The CMM data consist of about one hundred coordinates which are connected to each other by lines. The curves show how the probe has been swept over the walls. Some straight lines at the floor level forms the small room in the reception area. These lines follows the outer boundary of the sheet metal sleepers, compare with Figure 1. The door opening to the right in the figure leads to the cloakroom. The data is sparse compared to the point-cloud from the laser scan but compared to the manual measurements it’s rich. The point-cloud consist of 45 million coordinates and gives a detailed depiction of the installation environment (Figure 4B). Details such as windows, door openings and other objects can easily be detected in the cloud. In this scan the whole captured environment can be seen.

A B

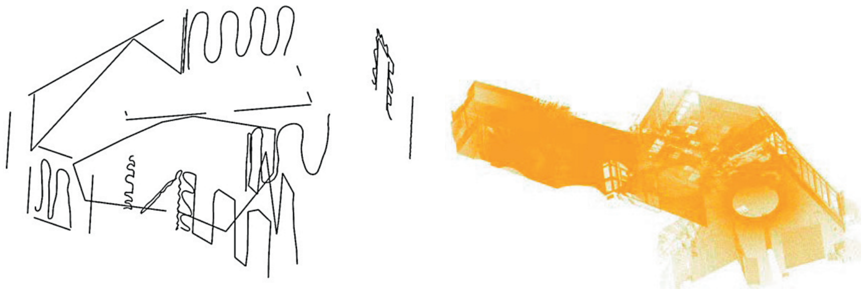

Figure 4. A: The figure shows the raw CMM data. B: The point-cloud of the construction site.

Figure 5 shows the placement of the pillar in the reception/visitors area in the both the supplier's 3D model (grey solid) and the super positioned point-cloud (orange dots from the point-cloud). The results show that there is a deviation between the model and the point-cloud. There are two circles showing the offset, approximately 18 millimeters, between the model and the point-cloud. The joinery-products supplier was providing a sofa that should lie adjacent to the pillar, with the backrest of the sofa to fit tightly to the pillar. The offset in positioning of the pillar was parallel with the sofa, and in this case, it was not critical to the fitting of this particular joinery product, but it did create an aesthetic problem. However, the offset in positioning of the pillar could have been more severe, which could have led to extra work in order to adjust the sofa to fit its environment. The pillar is the same as that shown in Figure 3. This shows that it is very difficult to measure the center position of circular geometry by manual methods.

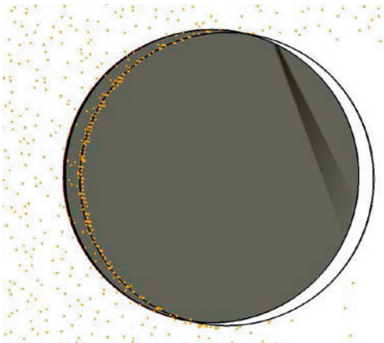

Figure 5. The figure shows a pillar in the supplier's 3D model in superposition with the point-cloud. The distance error between the point-cloud and the pillar is approximately 18 millimeters.

Figure 6 shows the sheet-metal sleepers where the walls for the reception area were to be erected. The sheet-metal sleeper in the supplier's model (black lines) has an offset from the point-cloud data. The green lines are used to highlight the sheet-metal sleepers from the point-cloud. The outer shape of the sheet-metal sleeper is captured with the CMM and shown in red. It can be seen that point-cloud data and the CMM model coincide quite well. The supplier's model shows an angular deviation of approximately 0.5 degrees compared to the other two models. It may not seem like much, but over a length of 2.3 meters, the deviation is approximately 20 millimeters. Such uncertainties, due to erroneous measurements, has effect on the efficiency on the on-site assembly since these errors become evident and need to be solved.

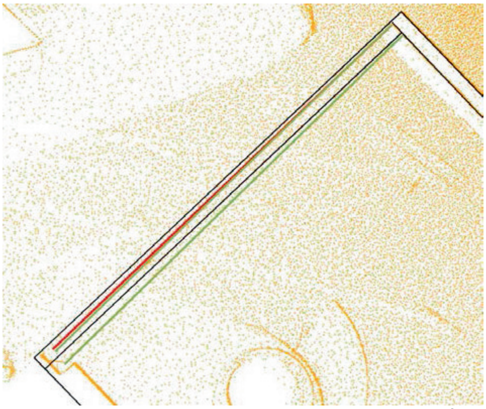

Figure 6. The figure shows the supplier's model positioned over the point-cloud of the small room in the reception area.

Figure 7 shows the supplier's model super positioned in the point-cloud. On the wall, a wedge-shaped part of the point-cloud disappears into the model. The deviation between the model and the cloud shows that the suppliers model is not accurate and can cause problems when installing products. Since the products are modelled from 2-D drawings, 3D spatial deviations are handled with *ad hoc* solutions in order to adjust the product; *e.g.*, to install wall panels on this wall, the assembly personnel will have to mount a batten to compensate for the shape of the wall. By using 3D data, these deviations could be taken into consideration when producing joinery products, which could help during the installation of the products.

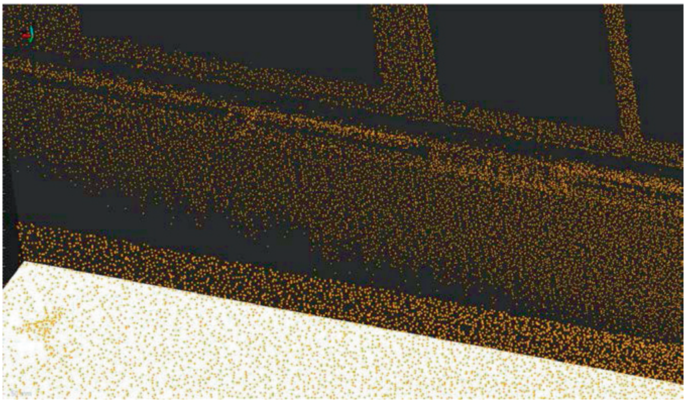

Figure 7. The figure shows the 3D model from the supplier super positioned in the point-cloud, in the reception area. In the point-cloud data, the windows are seen; the light part at the bottom of the picture is the floor.

By comparing the CMM model (gray) to the supplier’s model (green), it can be seen that the supplier’s model is a simplification of the geometry the small corner has been neglected (Figure 8). There is also an offset of 102 millimeters between the placements of the walls.

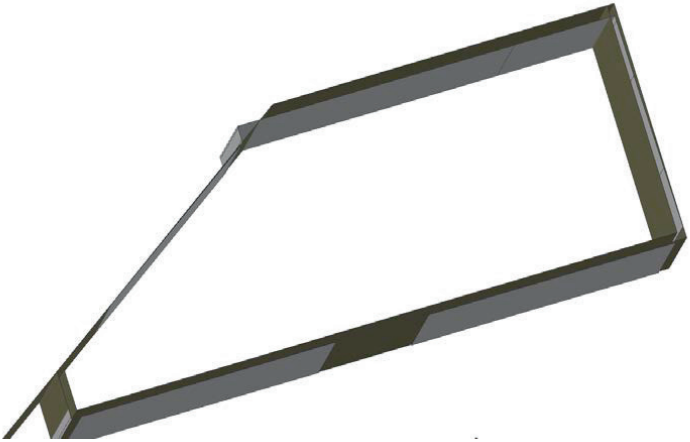

Figure 8. The 3D model, created from CMM data, of the small room in the reception area super positioned with the joinery-products supplier’s 3D model.

The comparisons between the supplier’s 3D CAD model and the CMM model and point-cloud data show that there are considerable dimensional differences (Figure 6). The deviation between CMM and laser-scan data is less than either of those two compared to the supplier’s model. The noise depth in the point-cloud is measured to approximately 4 millimeters, which is analogous with the manufacturer’s data. This means that the wall in the cloud could be placed somewhere within this noise. The inaccuracy of the CMM is, according to the manufacturer, less than 1 millimeters up to 5 meters’ distance. This implies that the supplier’s model is the one that deviates most from the actual geometry. The cause of the deviations in the supplier’s model probably derives from the manual measurements taken, the uncertainty of manual measurements and the accuracy of the tools used for acquiring the measurements. Even if the errors introduced by the equipment are considered, the difference between the 3D models and the model used for production is as much as 20 millimeters. This shows that the dimensional verification that the joinery-products supplier bases its production on is inaccurate. Besides the dimensional errors, the production preprocessor cannot adjust the joinery products according to the actual shape of the walls. The joinery-products supplier’s machinery can produce products with sub-millimeter precision. However, the low quality of the dimensional verification makes it difficult to utilize this precision. The density of manual measurements is also very limited, resulting in a weak basis for the production pre-processing.

3.4 Analysis of the studied 3D methods

The question is whether the problem observed with the current method can be improved by using 3D measuring technology. The biggest problem with the current method is the man-hours spent determining which measures are important, acquiring these measures and still being unable to produce products that fit without time-consuming alterations during on-site assembly. Comparing the method for manual measurements with the 3D techniques suggests that many of the issues with manual measuring can be avoided. 3D techniques negate the need for predetermined dimensions; the whole environment is captured with a laser scanner, whereas the CMM captures both walls and floors.

Since the whole environment is captured, all dimensions can be verified, thus eliminating the need for time-consuming complementary measurements. Reading dimensions and the manual communication of them will become obsolete, since the models carry that information. An obvious benefit when measuring with 3D techniques is the possibility to achieve accurate information such as center positions of pillars and the radii of curved walls. These techniques also enable the joinery-product supplier to reverse-engineer the installation environment for its joinery products in order for them to fit without the need for on-site alterations. By altering the product in the computer, the fit of the finished product is achieved during manufacturing instead of during assembly. The increase in quality will lead to faster assembly time and less reproduction of faulty products and the production capacity saved can be used for more projects for the joinery-products supplier.

Measurement errors are still present, but they are consistent through the model. The 3D information acquired contains spatial information on the environment such as angle between floor and wall, and “true” shape of walls and can easily capture radii. The 3D techniques tested in this study capture data faster than the manual method, but require after-processing of the data to produce models where measuring can be performed. The point-cloud from the laser scan can be used to fit 3D cad models of the joinery products without the need of first creating a model of the point-cloud. The benefit is time savings, and that there is no alteration of the data. The spatial 3D information acquired is digital, making it easy to disseminate to all the actors in the internal supply chain. Digital data are less prone to contain other measurement errors than the noise from the equipment itself, which can be more easily controlled than faulty measurements from the manual method.

A paradigm shift is needed in order to make the process more efficient. The surveying must go from 2D to 3D, and in order to make use of the 3D model of the installation environment, the joinery-products must be modelled in 3D. New tools and software have to be introduced, which requires education of the personnel and/or new personnel. When the new work method has become habitual, the joinery-product supplier can start to reap the benefits of the new 3D techniques.

5. Conclusions

Manual measurement methods entail dimensional uncertainties that create an insufficient basis for manufacturing joinery products. Products today are produced to be altered during assembly because of low level of spatial information on the installation environment. By reverse-engineering the on-site environment with 3D technology, producers will have a better basis for the manufacturing and final assembly of the joinery products. By fitting a 3D CAD model of the joinery-product into a 3D model of the installation environment, it is easy to adjust dimensions to ensure a good fit. By taking care of uncertainties during the production instead of during on-site assembly, the level of prefabrication can be increased. 3D measurements are not a way to achieve exact as-is dimensions, but the errors originate from noise, rather than from uncertainties due to human error, and are easier to handle when modeling. The errors are on the order of a few millimeters and are a closer mesh with the ability of the production lines the joinery-products suppliers use. A 3D depiction of the environment would have all dimensions, thus eliminating the need for complementary measurements. This will, however, place greater demands on the coordination between the joinery-products supplier and the construction contractor.

Joinery-products suppliers might not have understood the full potential, or have the knowledge or economy for investing in these technologies or recruiting skilled personnel for creating a good 3D basis for production. Finding a niche for consultants that could offer this service would be beneficial for Swedish joinery-products suppliers. The consultant doesn't need to know which dimensions are critical for the design. By capturing the entire spatial environment with 3D techniques, the important dimensions can be determined later by the production preprocessor. The production preprocessor doesn't have to spend time on deciding which dimensions are important to capture. The findings of this study should be applicable for other subcontractors supplying for the construction industry. It could also be argued that if different subcontractors would use a consultant to scan the environment, time could be saved by fitting products more efficiently as well as using the 3D data for more advanced planning tools, such as 4D CAD and Line of Balance as proposed by Björnfot and Jongeling [11].

Manual measurement is time consuming and often requires two persons; by surveying with a laser scanner or CMM, surveying can be performed by one person and be accomplished faster. The CMM requires after-processing to create measureable models, but if a laser scanner is used, 3D CAD models can be compared with the point-cloud to verify the fit of the product.
By introducing 3D technology, the spatial as-built uncertainties could be reduced and allow an increased level of prefabrication.

Future work
How to introduce 3-D measuring technologies and increase the use of 3-D CAD modelling in this industry with small sized companies with low level of education need to be investigated. Software has to be explored in order to find suitable solutions for the companies. The process has to be more standardized or automated to capitalize on the benefits from these of 3D digitizing techniques.

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