Suggestions for Innovation in the Supplying of Joinery Products Through the Application of Lean-Thinking and 3-D Sensing

Samuel Forsman

Wood Science and Engineering
DOCTORAL THESIS

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Samuel Forsman

Luleå University of Technology
Department of Engineering Sciences and Mathematics
Division of Wood Science and Engineering
Abstract

The supplying of engineer-to-order joinery products to the construction industry is a novel research area in both the wood-related and the construction-related fields. The process of supplying the construction industry with highly refined one-of-a-kind wood products is here examined in order to explore possible process innovations to identify factors contributing to inefficiency, to define areas for innovation to improve industry performance, and to evaluate 3-D sensing technologies as a way of achieving a model-based joinery production. The organizations studied use a mixture of concept-to-order and design-to-order production strategies to produce what in this thesis are called engineer-to-order joinery products.

The main consumer of the engineer-to-order joinery products are the construction industry, an industry that 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 to increase the degree of industrialization in the construction industry, and this is reflected in the research approach adopted for the work described in this thesis.

The conditions for supplying engineer-to-order joinery products to the construction industry have been studied and areas for innovation efforts are suggested. The primary research question has been: Can new technology and new management methods be applied to improve process efficiency and efficacy in the supplying of engineer-to-order joinery products? Lean principles and 3-D sensing are two perspectives chosen to investigate this supply process. The study has used both qualitative and quantitative research methods, with a slight overweight towards the qualitative methods, as the context for the quantitative research has always been in focus. Real-world case studies have been used for the empirical data collection.

The results suggest that there is a significant potential for increasing efficiency and efficacy through: greater focus on cross-organisational innovation focusing on higher levels of industrialisation, new forms of contractual relations, supply chain cooperation, improved knowledge-transfer and information management, developing competence on 3-D sensing and “BIM”-modelling, and through organisational consolidation.
Sammanfattning

Att leverera snickeriprodukter som designas och utvecklas mot kundorder (engineer-to-order) är ett låg utforskats forskningsområde i gränslandet mellan träforskning och byggrelaterad forskning. Processen att leverera högt förädlade "one-of-a-kind" träprodukter har i denna avhandling studerats med syfte att utforska möjliga processinnovationer genom att identifiera faktorer som bidrar till ineffektivitet, att definiera områden för innovation som kan förbättra industrins prestanda, och utvärdera 3-D mättekniker som en metod att minska byggarbetsplatsens rumsdimensionssäkerhet och att genom detta åstadkomma en modellbaserad snickeri-produktion där produkterna anpassas till rummen i den digitala modellen för att sedan tillverkas med numeriskt styrda maskiner. De studerade organisationerna använder en blandning av produktionsstrategierna “concept-to-order” och “design-to-order” för att producera det som i denna avhandling kallas kundorderutvecklade snickeriprodukter.

Byggindustrin som är den huvudsakliga kunden till dessa snickeriprodukter har kritiserats för att inte hålla jämn steg med annan produktionsindustri när det gäller kvalitet, kostnadseffektivitet, innovation och produktionsmetoder. Tillämpandet av Lean produktions-principer och supply chain management är innovationer som vanligen föreslås för att öka graden av industrialisering inom byggbusiness vilket också återspeglas i forskningsansatsen för arbetet som beskrivs i denna avhandling.


Resultaten visar på potential för betydande ökningar i effektivitet och uppfyllande av kundförväntningar genom: ökat fokus på innovation över organisatoriska gränser för ökad grad av industrialisering och effektivisering, nya former av kontraktrelationer och supply-chain samarbeten för förbättrad kunningsöverföring och informationshantering, utveckling av kompetens inom 3-D rumsöverföring och BIM-modellering samt utveckling av den organisatoriska strukturen.
Preface

This work has been performed at the division of Wood Technology at Luleå University of Technology, Department of Engineering Sciences and Mathematics, and has been supervised by Professor Dick Sandberg and previously by 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 Manufacture) and the Swedish Governmental Agency for Innovation Systems, Vinnova. This supervision and funding 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. These and other interview respondents have been an invaluable asset in sharing their experiences and knowledge. They are all gratefully acknowledged.

Through the journey towards this PhD thesis, both life and work have had their ups and downs, but in the end the continuous effort forwards was the winner and the challenges faced made the journey more educative, adding a dynamic that is characteristic for an interesting journey. The co-authors of the papers in particular and my colleagues in general have contributed to the forward momentum on this journey and are greatly acknowledged.

Finally, I would like to thank my family and friends for their love, comfort, and fun; my dear children Lukas and Alice, who give me such joy and comfort; my father and mother for their support and encouragement to pursue my life’s dream in Kittelfjäll; and all my skiing, cycling and adventurous friends for all the fun things to do with you that have shown me that the world is much more than research at the office, out there is GEMBA!

Skellefteå, June 2016

Samuel Forsman
List of appended publications

This thesis is based on the following papers listed in chronological order and referred to in the text by their Roman numerals.


Author contribution to appended publications

I) Interaction in the construction process: System effects for a joinery-products supplier
   Forsman’s contribution was to plan, perform, and analyse the interview study together with the literature study. The paper was written mainly by Forsman, with help in the methodology and final analysis from Bystedt, and with feedback and critical response from supervisor Öhman.

II) Need for innovation in supplying engineer-to-order joinery products to construction: a case study in Sweden
   Forsman’s contribution was to plan, perform, and analyse the interview study together with major parts of the literature study. Most of the paper was written by Forsman with contributions from co-authors in the Information Modelling and Method chapters. The final analysis was performed by Forsman and the co-authors, with feedback and critical response from supervisor Öhman.

III) Model-based production for engineered-to-order joinery products
   Forsman’s contribution was to plan, perform, and analyse the interview study. Most of the paper was written by Björngrim with major contributions from Forsman in the Results & Discussion chapter. The final analysis was performed by all the authors.

IV) Real-World Three-Dimensional Measuring of Built Environment with a Portable Wire-Based Coordinate-Measuring Machine
   Forsman was the sole author of this paper.

V) Three-dimensional, as-built site verification in supplying engineer-to-order joinery products to construction
   The authorship was a close partnership between Forsman and Laitila. Forsman contributed with most of the data-collection from the studied case, CMM measurement and analysis. Laitila performed all in-house point-cloud modelling and both authors analysed the point-cloud data, CMM-data and manual measurement analysis and authored the paper, although Forsman contributed mostly to the authorship.
Not everything that counts can be counted
and not everything that can be counted counts.

William Bruce Cameron
Informal Sociology:
A Casual Introduction
to Sociological Thinking
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References
1 Introduction

This chapter presents the motivation of the research, and the purpose, objectives, and demarcations defining the research.

The process of supplying the construction industry with highly refined one-of-a-kind joinery products is 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 means that engineering is required in the supplying of these joinery products, and consequently these are considered as engineer-to-order (ETO) products.

In the work described in this thesis the supplying of ETO joinery products has been studied from a process efficiency perspective, related to the strategic target area of developing industrial leadership through efficient processes in the National Research Agenda for 2020 (NRA Sweden, 2012) of the Swedish Forest Industries Federation. Joinery products are a major contributor to what is classified as building components, which alone stand for 19% of the woodworking production value in the European Union (Eurostat, 2016). Traditionally, building components such as windows, doors, stairs, entrances, interiors, and kitchens are designed and manufactured by joinery-product suppliers.

The distribution value streams of these joinery 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 these products. 2) The second value stream, which is the focus of this thesis, supplies the construction industry with tailored and/or one-of-a-kind products that are fitted into a given building object. These joinery products are here called “ETO joinery products”. The process of this second value stream is adapted to and resembles the culture and situation in the construction industry, and it has thus not been able to fully utilize industrialized processes in terms of cost efficiency, innovation, and production methods.

Situation in Construction

The current state of construction is being debated in the media as well as in the research community. 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 reduce the cost of building production and alterations have gained much attention due to their effects on the costs of living and working environments. One effect of the
prevailing high costs is decades with a low housing production that have led to a
great need for new housing production. Swedish prognoses show that between
2012, and 2025 there is a need for 558 000 new Swedish homes, i.e a need of an
annual average production of 39 900 new homes with peaks at 50 000 between
2012 and 2018 (Boverket, 2015). For comparison, the annual production of
homes during the last twenty years has been between 20 000 and 30 000
(Statistics Sweden, 2013b).

In several publications as well as within the Swedish construction industry,
increased industrialization is mentioned as one possible way to solve 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 construction problems has
also been investigated internationally in an attempt to reduce non-value-adding
craft-based activities and to 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
though a systems approach is needed. For this purpose, construction researchers
have directed this attention towards the manufacturing industry in an attempt to
learn and adapt, or in some cases even copy, successful concepts such as
computer-integrated manufacturing and lean production.

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 can often be characterized as a more
traditional construction set-up and that 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 take part only in some of
the phases of the process (Anheim, 2001; Vrijhoef & Koskela, 2005). Joinery
products are in general 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**

Many 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 as a series of
individual activities, but only a few have a track record of consistent and
significant success (Vrijhoef, Koskela, & Howell, 2001; Azambuja & O'Brien, 2008).

Traditionally, the price has been the dominating factor determining 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 hamper innovation (Aouad, Ozorhon, & Abbott, 2010). Therefore, it is recommended that managers in construction realize that the establishment of a cost-effective and responsive network of suppliers is needed if customers are to be provided with products more cheaply and faster than by their competitors (Nasr-Eddine Dahel, 2003).

There are several studies of the supply-chain management in construction (SCMC) focusing on e.g. pre-engineered metal building manufacturing, electrical switchgear, elevators, and aluminium windows, etc. (Akel et al., 2001; Arbulu & Tommelein, 2002; Elfving, Tommelein, & Ballard, 2002; Azambuja & Formoso, 2003; Fontanini & Picchi, 2004), but studies of the supplying of one-of-a-kind joinery products to the construction industry are rather limited. One example, however, is a Brazilian study on the supply chain of prefabricated wooden doors, which concludes that information deficiencies and a lack of system integration can eliminate 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 engineer-to-order joinery products**

Supplying the construction industry with highly refined one-of-a-kind joinery products means that engineering is required in the supplying of these joinery products, and these are consequently considered as engineer-to-order (ETO) products, where “engineer-to-order” refers to uniquely designed products being engineered to fit specific needs. With a wide range of assignments, the novelty of the assigned work determines whether a concept-to-order or a design-to-order (Winch, 2003) production strategy is to be used.

In general, ETO joinery products are ordered by a construction contractor but are often prescribed by an architect translating a client’s wishes into construction documents. The undertaking of the supplier of ETO joinery products normally includes assembly of the product on the construction site. The joinery products are more prefabricated than general on-site construction work, but there are still limitations on the prefabrication level and assembly is a major consumer of the ETO joinery-product supplier budget. Therefore this thesis seeks to increase the
understanding of the ETO joinery-product supply process and to explore possible process innovations.

Hereinafter only ETO joinery products are in focus and they are referred to simply as “joinery products”.

1.1 Purpose and objective
This work investigates the process of supplying of joinery products with a Lean-principle perspective and 3-D sensing perspective. The intention is to explore possible process innovations.

The objective is to identify factors contributing to inefficiency, to define areas for innovation to improve this industry, and to evaluate 3-D sensing technologies as a tool to achieve a model-based joinery production.

The research questions form the basis for selecting a research strategy (Yin, 2003). Miles and Huberman (1994) advocate dividing the objective into questions in order to more easily delimit the appropriate theoretical and empirical conceptual framework for the research project. The overall research question in this thesis is simply:

- Can new technology and management methods applied in the supplying of joinery products be used to improve process efficiency and efficacy?

This question contains three key components of interest.

1. The process of supplying joinery products.
   The research experience and literature on the supplying of joinery products were limited and therefore needed exploration.

2. What management method should be applied?
   The much recognized Lean-thinking principles were chosen as an analytical frame of reference for the study of the supplier process.

3. What new technology should be applied in the supply process?
   On-site measurement before the production of the joinery products was an issue raised by the suppliers within the study. It was therefore decided to investigate the applicability of 3-D sensing technologies.

With these three components in mind, the following explorative research questions were formulated to understand the process of supplying joinery products.

- How are joinery products supplied to construction (i.e., by what process)?
- How is the supply-chain relationship between a joinery-products supplier and the construction process arranged?
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- How do the actors in the supply chain interact with each other?
- How can 3-D sensing technology support the process of supplying joinery products to construction?

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

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

By answering these questions based on empirical data and a theoretical frame of reference, this thesis answers the overall research question and initiates a discussion as to how to innovate the process of supplying joinery products to construction.

1.2 Demarcations

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

Although this thesis considers the overall process of supplying joinery products to construction, the focus is on interactions with the construction process, on the efficiency restraints which arise late in the process, such as in the assembly, and on the applicability of 3-D sensing technology. The search for the reasons for these restraints focuses on the value stream.

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

The study is related solely to Swedish cases and thus represents that country’s specific cultural situation. Despite this limitation, many of the examples found in the global research literature seem also to be applicable to the Swedish construction culture.
1.3 Joinery Production in a Sustainable Society Context

The development of a sustainable society is a global challenge that has become an important issue on the political and business agenda. The woodworking industry is in a position to make a significant contribution to this global challenge. The following shows how this thesis contributes to this challenge:

The political importance of a sustainable society is reflected in the strategic objectives set up for the European Union (EU) that have at their heart three priorities: smart, sustainable and inclusive.

Society is striving for social responsibility in business models, for solutions to climate change, for the sustainable use of natural resources, for innovation that expands the use of renewable resources, for markets that respect nature, and for new ecosystems services that raise the economic value of renewable natural resources. A sustainable society balances the three perspectives: of social, environmental and economic sustainability to maintain the opportunity for society growth in the future. The forest products (wood, pulp and paper) industry model may hold the key to reaching these aims, bringing answers to many of the questions society has to face. In the following, the woodworking (wood and wood products manufacturing) perspective for a sustainable society and its contribution to this are discussed with a focus on European and Swedish experience.

Using wood in the products we use in our daily life is a good choice due to its combination of renewability and biogenic origin. The challenge for the wood-products industry is to increase its competitiveness, find more applications in the society and to increase the general awareness of the society-beneficial properties of wood and wood-based materials (NRA Sweden, 2012).

From a social perspective the woodworking industry is a major provider of welfare and it employs millions of people in the European countries and features among the top three industries in Austria, Finland, Portugal and Sweden. This industry is a supplier of homes and products for the living and working environment that have a low climatic impact and come from a renewable natural resource which is sustainably harvested. The industry is acting responsibly for the environment, for their employees and their working environment. Further wood is a material with “biophilic” properties (Wilson, 1984), to which human beings have an innately emotional affiliation. It has also been shown that wood as a natural material possesses pro-health benefits such as stress reduction within the autonomic nervous system (Fell, 2010; Augustin & Fell, 2015).

From an environmental perspective, global warming is the major environmental issue of our time. A more extensive use of wood can significantly reduce these problems due the absorption of CO₂ from the atmosphere through photosynthesis in the growing trees, turning carbon into wood. When wood is
used in products, this carbon is stored within the product throughout its serviceable life. Thereafter, wood products can in most cases be recycled, extending the carbon storage effect, and/or be used as a carbon-neutral fuel as a substitute for fossil-based fuels. Thus any increase in the global volume of carbon storage in wood products will reduce the CO₂ in the air, an effective means to reduce climate change.

From an economic perspective, the woodworking industry is a driving force in the global economy. Within the 28 European Union member countries (EU 28), the woodworking industries (NACE Rev. 2 divisions C16.1, C16.2, C31) annually total more than EUR 200 billion, 2010–2013 (Eurostat, 2015a). E.g. in Sweden, the forest industries (woodworking, pulp and paper) have the largest net export value of all industries and account for 9–12 per cent of the Swedish industry’s total employment (Swedish Forest Industries Federation, 2015). The woodworking companies are often located in remote, less industrialized or developed areas, and thus make an important contribution to the rural economy. The companies within the woodworking industry are mostly SMEs, with only a few large groups, typically in softwood sawmill and panel and parquet sectors operating on a European or global scale. The vast majority of the woodworking products find their way into the construction sector and therefore make a significant contribution to a sector that represents the sixth largest contributor to value added in the EU Member States and about 10% of the GDP (Eurostat, 2015b).

In the National Research Agenda for 2020 (NRA2020), the forest-based industry in Sweden envisions that in the middle of the 21st century the conversion to a bio-based social economy will have been implemented. For the 2020 horizon, crucial steps have been taken on the road to climate adaption and sustainable utilisation of the earth’s resources. To reach this situation, 19 national strategic themes are formulated distributed into four strategic target areas – Bio-economy, Raw material, Processes, and Products.

This thesis contributes to one of these four strategic target areas, the Process area, where the aim is to develop industrial leadership through efficient processes. Through this, the woodworking industry can improve productivity and therefore be more competitive in offering products from a renewable material with a low carbon footprint.
Introduction
Method

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 process. Both quantitative and qualitative methods have been. Since the researcher is an important instrument in the latter, the researcher’s background is presented. Finally, a discussion of validity and reliability is presented.

2.1 Research approach
When seeking to improve the efficiency of the supplying of 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 information about this type of industry in the literature and in the research community. Therefore explorative research was needed and qualitative methods were judged to be appropriate.

When this research project was being defined, industry representatives of the Swedish joinery product suppliers raised the need for accurate as-built spatial information. An hypothesis was put forward 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. Therefore, explorative research on 3-D sensing technology was chosen, using both qualitative and quantitative methods to validate this technology and to understand its applicability in the context of supplying joinery products.

Based on the 3-D sensing idea, senior division researchers obtained a coordinate measuring machine (CMM) able to perform geometrical measurements in three dimensions and to export this information to CAD software. At first, a quantitative approach was taken to validate the performance of this machine. Later, cases were established to gain experience of spatial measurement with the CMM and of the process of supplying joinery products to construction. This was done in cooperation with a major Swedish joinery products supplier who informed the researcher of “real world” cases (Robson, 2002) that needed special attention with regard to spatial as-built verification before production. As the process continued, it became clear that it was not 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 measurement equipment on the process of supplying joinery products, a greater understanding of the process of supplying joinery products to construction was required. It was realized that interviews were needed to gain further understanding, and a change to a more qualitative approach was therefore necessary to enhance the understanding of the premise.
Method

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 greater qualitative experience was garnered to jointly explore how to approach this area of research, and this led to papers I and II.

Thereafter, the focus was on the 3-D sensing concept. The idea was developed and experiences from the explorative cases were used to exemplify how the 3-D sensing information could be used in the joinery product supply process. The 3-D sensing technologies, mainly CMM and laser scanning, were then evaluated in a number of real world cases together with performance tests in a laboratory environment. Here quantitative methods were used to evaluate the performance of the 3-D sensing tools and qualitative methods were employed to understand the measurement needs in the context of supplying joinery products. An important step has been to understand the way in which the measurement data must be processed to make the information usable in the supplier process.

When a phenomenon is studied 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>
<thead>
<tr>
<th>Role of Theory Approach</th>
<th>Quantitative</th>
<th>Qualitative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epistemology</td>
<td>Deductive</td>
<td>Inductive</td>
</tr>
<tr>
<td>Theory of knowledge</td>
<td>Positivism, natural science, explaining</td>
<td>Interpretivism, hermeneutic, social science, understanding</td>
</tr>
<tr>
<td>Ontology</td>
<td>Objectivism</td>
<td>Constructivism</td>
</tr>
<tr>
<td>Theory of reality</td>
<td>Verification of theory or hypothesis</td>
<td>Generation of theory and model</td>
</tr>
</tbody>
</table>

It can be seen in Table 1 that these quantitative and qualitative paradigms have different natures and views on knowledge and reality; for example, the epistemological debate as to 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
Method

reflects the distinctiveness of humans, where an interpretive understanding of the social action is sought for in order to casually explain its cause and effect (interpretivism) (Bryman & Bell, 2007). Furthermore, the quantitative and qualitative approaches differ in their views as to whether social entities can be considered to be 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, first 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 is the nature of the research path in this thesis. Here qualitative methods dominated in the beginning but then reached areas of a more narrow nature where more quantitative research was applicable, an approach that can be described as abductive (Figure 1) rather than purely deductive or inductive.

![Figure 1. Research approaches (Nordvik, 2008, adapted from Alvesson & Sköldberg, 2000)](image)

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 is characteristic of the research in this thesis, since the empirical material has been examined with an open mind at first and then analysed against appropriate theory. When more theoretical enlightenment had been attained, the empirical context was once again approached. Furthermore, the study uses a systems approach, in that individual parts of the studied processes have not been 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).
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 presents the nature of the research questions, and it can be seen that these questions, in addition to being explanatory, have a predominantly how and why
nature. Furthermore, the control of 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), and it is unwise 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 and in the choice of data collection techniques, and of his/her personal influence on the analysis and conclusions are means to reduce the possible biases (Merriam, 1994). In this thesis, quantitative and qualitative methods have been used and the researcher’s background is therefore presented to give the reader an opportunity to assess 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 different 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 obtained an MSc in Wood Technology and gained experience in developing processes and products relating to 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 backgrounds 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 phenomena from various perspectives as well as through 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 relate 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 which 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, 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: “the waste (according to the Lean definition) 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 identify and describe deviations from Lean principles and other problem areas in information validation.

Four case studies were also conducted using a coordinate measuring machine (CMM). Here both quantitative and qualitative methods were used. The first method was used to evaluate the accuracy of performance of the CMM when used in the context of supplying joinery products, in order to understand the need for information of on-site as-built geometries in the supplier process and how the performance of the CMM meets up to these needs. In these cases, the unit of analysis was: “CMM construction site measurement and 3-D model generation in a joinery products supply context”.

This type of research design is seen as ‘abductive’. After gaining knowledge from early empirical results, the researcher learned new facts that were then considered from different theoretical standpoints, e.g. Lean production, Lean construction and 3-D sensing. This meant that the researcher could expand the theoretical knowledge and understanding in the empirical context as the study progressed.

Yin (2003) emphasises the importance of thoroughly describing all research procedures to enable the reader to form his/her own opinion about the reliability
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and validity of the results. The research design has elements of flexible design (Robson, 2002), as the design has evolved as the research has proceeded. 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

Figure 3 presents a schematic representation of the research process described in this thesis. The research consists of empirical studies of supplier processes, the development of the conceptual idea of joinery production based on 3-D models from 3-D sensing data, and 3-D sensing with a coordinate measuring machine and a laser scanning machine. From the five appended papers, selected results have been extracted and a cross paper analysis is made in order to answer the research questions included in the cover paper. A brief description of the rationale for the five empirical studies performed within this research project and the associated appended papers is presented here.

2.3.1 Paper I

The research in Paper I was initially of a quantitative nature, seeking to validate the 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 which 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 sensing technology — the coordinate measuring machine Proliner 8— 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. Firstly, a limited section was 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 submitted 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.

The qualitative part of the case study 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 contact with various people involved in the supplier project. 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, but questions outside the guide were also asked during the interviews depending on 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 three to seven questions, open in character and with possible sub-questions or new questions arising during the conversation. The main areas of interest in the interview questionnaire were 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 measurement equipment
- Pros and cons of the project as experienced by the respondent

The respondents in the interviews were practitioners in the construction project studied, and from companies to which the joinery products were 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 were held with 18 persons, 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 was documented in order to facilitate an 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 folders.

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 study was 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 were 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 covered 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 on-site assembly in order to reveal
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any problems arising 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 makes it possible to make sense in a wider context and
draw conclusions that individual persons may have difficulty in 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 made 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 made it possible to reflect on specific situations in retrospect and to
compare them with what was said in the interviews. The on-site observations
also made it possible to gather 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, 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 purpose 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, but with a weighting towards the material from the second
The analysis was focused on defining different types of waste surfacing in the studied cases and possible areas of innovation, where the information flow and knowledge exchange across organizational borders was of special interest. The causes of these problems were analysed and generalised using the principles of Lean production and supply-chain management. To improve the productivity of joinery product companies, ways to improve the internal process through Lean principles, modelling of information, supply-chain planning, and coordination were explored.

2.3.3 Paper III – Model Based production...
In this study, the focus was on gaining a detailed understanding of the information flow in the joinery product supply value stream. The studied case was the same case as that reported in Paper II, and the qualitative methods and data collection described there therefore also apply in this paper. Here, special attention was paid to information carriers and the quality of their information and how reliable as-built information can form a base for a Building Information Model (BIM), and the case experiences were used to explore process areas where this information can enhance the process and to suggest a new process layout and the information needed to support this setup.

2.3.4 Paper IV – Real-World Three-Dimensional Measuring....
In the fourth paper, the focus was on 3-D sensing of as-built construction site geometries with the Proliner, a portable wire-based coordinate-measuring machine. The context is the supplying of joinery products. Both quantitative and qualitative methods were used in an abductive manner as the experience of practical use increased the understanding of how to measure performance quantitatively. The qualitative methods described in Papers I and II also apply in this paper since these cases were also studied with the 3-D sensing perspective. In addition, two more case studies were performed with the same principles.

The CMM capability has been evaluated against the two main criteria of accuracy and usability, to determine whether it can perform for as-built site verification in 3-D to a level where the fitting of joinery products can be performed in the digital domain during design. Both machine performance and case performance were studied and discrepancies were quantified and explained qualitatively.

2.3.5 Paper V – Three-dimensional, as-built site verification in...
Paper V focuses on obtaining as-built spatial information from the environment in which the joinery products are to be placed and fitted. This is information that the joinery products supplier needs before starting the production to verify the spatial information provided by the procurer. Two areas have been studied: the current practices and obstacles for the joinery products supplier in surveying the environment adjacent to the products, and the use of 3-D sensing technology that is more advanced than the technology currently used by the joinery products
supplier studied in the “real world” case (Robson, 2002). The supplier project studied was the same as that studied in Paper II, but in this case the analysis of the current practices in the process was 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 sensing technologies was applied to the same physical objects and at the same time on the same day as the surveying performed by the joinery products supplier. The 3-D sensing with CMM and the laser scanning technology 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 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 the extent to which 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 cases have aimed to be explanatory, this becomes applicable in this research, and the use of a research framework — comparing our own empirical findings to those of other research — and theory triangulation are thought to enhance the internal validation of this study.

External validity relates to the possibility of generalising the results of the case study, where external validity concerns an analytical generalisation from empirical observations to theory rather than to a population as in a statistical generalisation when using a survey strategy for the research (Yin, 2003). Due to their nature of being difficult to verify spatially for the joinery products supplier which adds uncertainty to the projects, the cases chosen 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
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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 the 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 again, not on comparing the results of one case with those of a different case study, which would be difficult in the present case due to the one-of-a-kind nature of construction, which is the research arena in this study. Continuous diaries of the research work have been maintained, the empirical material is documented thoroughly through notes, voice recordings, and photographs, and during interviews an interview guide was used, all in order to enhance transparency and repeatability and thereby strengthen the reliability.
3 Results
In this chapter, the results of interviews, observations, photographs, voice recordings, and documents from the work reported in the appended papers are presented. Some of the material from interviews and observations can be found in those papers. Here, the appended papers are summarized, the process of supplying joinery products to construction is described, and the results in the appended papers are highlighted.

3.1 Paper overview

Paper I: Interaction the construction process. – System effects for a joinery-products supplier
In Paper I, the focus is on the interaction between the joinery products supplier and the construction process. Four main waste generators have been 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) the inventory of information documents breaks the flow of value-creating activities.

This study shows that interaction is hampered by poorly defined interfaces, a lack of standardization, and a lack of feedback on design and method information that is 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 supplier interfaces with the contractor organization, and also with the architect and the client. This calls for a different attitude towards the suppliers in construction, and more integration of contractors and suppliers in order 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 main two areas with a potential for improvement, in which there are numerous knowledge disconnection effects for the joinery products supplier.

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

Paper II Need for innovation in supplying engineer-to-order joinery products to construction
Paper II focuses on the supplier process itself, with special attention to problems arising late in the process. Two main areas are identified as being the cause of much of the waste:

- The procurement model
- The inadequate information standardization and communication
A procurement model based on a more long-term relation than that at the 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 the 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 in the suppliers’ own processes and appear during assembly. Assembly inefficiency problems can be addressed by the joinery product suppliers. Three major contributors to assembly inefficiency were identified:

- Inadequate planning and coordination
- The absence or, inadequacy of assembly information
- Spatial uncertainties

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

The absence or, inadequacy of assembly information, disturbs the flow and process efficiency. It would be possible to increase the efficiency of the assembly knowledge build-up through a 3-D modelling of the joinery products. Making the information easily understandable and usable in the assembly situation is an important way to improve the way in which the assembly is achieved.

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

**Paper III: Model-based production for engineered-to-order joinery products**

Paper III, is based on the findings in Paper II that deficiencies in information mediation are a major contributor to process inefficiency, and a model is produced for improving information management throughout the joinery product supplier process. The use of a 3-D modelling technology is shown to make possible the adoption of a Building Information Model (BIM) philosophy, providing tools for a better integration to the construction process as well as increased automation and planning within the joinery product supplier process.

Unlike traditional as-planned BIM, the supplying of joinery products requires a BIM based on as-built spatial information. Highly accurate as-built spatial
information is seen as a requisite to facilitate the digital product-to-room fitting of the products during the design instead of manual fitting at the end of the supplier process. This is where 3-D sensing is needed in the supplier process as a base for further development of automation in the supplier process.

The proposed model-based production has the potential to improve quality, efficiency, and sometimes also efficacy in all the supplier process steps, for example an easier understanding of the task in the sales process and the communication of suggested product solution comes based on the increased visualization which a 3-D model provides. The surveying can be enhanced with appropriate 3-D sensing technology and, in the production stage, the products can be better defined and fitted to the place where they are to be used. This fitting can then be performed physically during manufacture with numerically performed machinery. The 3-D model can also be used to improve the planning of the logistics, optimizing the product parcel packing for easy transport and on-site unloading and fitting to in-transport routes. The final assembly benefits from a better understanding of how to assemble through the 3-D visualization, more prefabricated products with less manual product-to-room fitting, and a process that is fitted to the construction project, where the products are to be supplied using 4D/n-D information modelling.

**Paper IV**

Paper IV focuses on 3-D sensing for as-built dimensional site verification with the Proliner, a portable wire-based coordinate-measuring machine, related to the supplying of joinery products to the construction industry. Currently used methods for as-built site verification leave uncertainties with respect to the as-built geometrical conditions. This leads to a number of types of waste in the supplier process: unnecessary transport, motions, waiting, over-processing, over-production, and defects. Much of this waste can potentially be eliminated through automation actions based on BIMs with accurate as-built geometries and with the semantics of the construction process.

One way of increasing automation is by using BIMs to move the product-to-room fitting from the end of the process to the early stages when the products are being designed. The performance of the tested CMM has therefore been evaluated with regard to its ability to provide reliable as-built construction site dimensions in 3-D to a level where models of the joinery products can be made to fit in the digital domain before the manufacturing.

The CMM has three sensors which make it possible to determine the measurement position, one measuring the distance of the extracted wire, and the other two measuring the horizontal and vertical positions of the measurement arm. The test of the CMM sensor accuracy shows that the distance from the CMM to the measurement position, i.e. the amount of extracted wire, is the most significant source of the CMM random error. In the outer range of the
CMM, which is the position most used in practice, the random error of each individual measurement registration is with 95% confidence in an interval between 0.78 - 1.13 mm. This size of the error is on par with joinery product tolerances but do meet the requirements for the golden rule of metrology.

The CMM functionality to extend the measurement range by relocating the machine while keeping measurements before and after relocation in the same coordinate system is called Leap. When tested, this functionality gave individual mismatch errors significantly greater than the user information given by the machine, and serial Leap measurements lead to an absolute error that vastly exceeded accumulated individual mismatch errors. The directions of these errors were also irregular and they were therefore difficult to predict and compensate for.

The cases investigated have shown measurement errors considerably greater than the test of the sensor accuracy reports. Four factors were identified that affect the measurement accuracy in the studied cases:

- The accuracy of the measured coordinates
- The choice of coordinate positions
- Error leveraging
- The Leap Function

From a usability perspective, three main problems have been identified in the studied cases:

- Range and reach
- Limitations in “picturing” the construction site and its details
- Level of expertise needed to perform accurate measurements
- Processing of measurement data to measurable 3-D models

The hypothesis that as-built dimensional uncertainties on construction sites can be eliminated to a level on a par with joinery-product tolerances using the available CMM was therefore rejected.

**Paper V**

In Paper V, the process of retrieving spatial as-built information when supplying joinery products to construction is examined. The focus is on understanding how 3-D sensing technology on site can assist the process of manufacturing joinery products to fit construction requirements. The manual process and two types of 3-D sensing technologies have been evaluated: coordinate measuring with a Proliner 8 coordinate measuring machine (CMM), and laser scanning with a Leica Scan Station C10.

The focus is on understanding the current process of manual surveying and the possible applicability of 3-D sensing technology as means rationalising the
manufacture and supplying of joinery products. The frame of analysis of the 3-D sensing methods uses three criteria: (1) Improvement in current surveying. (2) Applicability, i.e., the possibility of adapting the technology to involve aspects such as information quality, measurement range, portability, reconstruction of 3-D geometries for measurement purposes, efficiency in performing measurements and subsequent data processing, and qualitative improvements in project information communication. (3) Potential for automatic product-to-room fitting considering the accuracy and detail of the model and possible surface reconstruction.

The study shows clearly that the currently used manual surveying methods leave uncertainties regarding the physical dimensions of a construction site, which limits the possibility of reducing the time and resources needed to assemble joinery products on site by moving the product-to-room fitting to the digital domain during product design and manufacture. The CMM has the potential to supply coordinate registrations on a par with the desired accuracy requirements for higher level of prefabrication, but it is only possible to obtain information for a simplified reproduction of a construction site, and this limits the possibility of achieving a satisfactory fitting of joinery products in the factory. CMM surveying cannot provide sufficiently accurate spatial information to achieve full product fitting during the design and manufacture of joinery products.

Laser-scanning surveying has the potential to capture most of the relevant details needed for a joinery-product manufacturer, but the challenge is to retain the information through the scan-to-BIM processing. The time and resources needed for point-cloud processing can be a problem from the joinery-product manufacturer’s perspective, due to the short time frame between access to the construction site information and the delivery data for the manufactured product. The frequent presence of topological surface irregularities combined with point-cloud noise depth and point-cloud density variations make it difficult to achieve measurement accuracy on a par with the tolerance demands on joinery products. Laser scanning seems to be applicable for the surveying required by a joinery-product manufacturer, but problems remain with the level of detail and accuracy needed to enable product-to-room fitting of joinery products already during design and manufacture.
3.2 The process of supplying joinery products

The process of supplying engineer-to-order joinery products to construction seen in the studied cases can be described by the value stream map in Figure 4. The first stage in the process is the sales effort in advertising and making quotes, and then when orders are received, production pre-processing refines the information in the order into a product definition and work orders. At the same time assembly work is planned and procured. After the product components have been manufactured they are transported to the construction site and assembled by an external contractor. In the following sections, this process is described in more detail together with observations concerning 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, and a design-bid-build project delivery (Forbes & Ahmed, 2011) is generally used, where the construction contractor requests quotations from joinery products suppliers for products that are often prescribed by an architect who provide drawings of the client wishes. The construction contractor requests quotations from possible suppliers either: (1) when the contractor is calculating a possible project and is required to submit a tender to a client in the early stages of the product determination stage, or (2) when the contractor has received a project from the client, i.e., in the late stages of the product determination. The quotation requests are often accompanied by detailed and complex regulations, and there are often detailed definitions and specific demands that are open to interpretation by both sides, and the contract form is a 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. The quotation requests are processed by a sales department that estimates costs and market value when submitting a tender.

Observed problems

In the studied cases, the procurement was at the project level and a long calendar time compared with the time taken for realising the product. For example, in one case, 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 another case, the relationship was
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60/40. Thus more calendar time is used for the procurement than for the actual realisation of the ETO product. In the procurement stage, much calendar time passes between the architect’s product definition and the joinery product supplier’s product definition, and this delay hampers the knowledge exchange between those specifying the value of the product and it thus affects the extent and quality of the design work, which in turn affects the level of prefabrication, since more of the problems is left to be solved in the on-site assembly with craftsmanship methods.

In the sales process, work is performed by several bidders but only one bidder gets paid for the work. This is an issue which has been discussed by other authors (Josephson & Saukkoriipi, 2005). Two important lessons can be drawn from this: (1) the time spent on submitting tenders that do not result in an order is an overhead cost that needs to be carried by successful orders, and (2) due to the overhead cost of submitting tenders, the work required for this is minimized with the risk of increasing uncertainties in the cost estimates. It is thought that competition will decrease costs over time but experience in construction has shown that the prices show an upward trend greater than that in other industries, with fluctuations mostly based on market conditions (Forbes & Ahmed, 2011, p. 25). This indicates that in the long run, the bidding process lacks incentives for improving the efficiency.

The problem is not the bidding process itself but the temporary nature of the business relationship. The extensive work for the business transaction in relation to its business value removes the focus from developing the interaction in the construction process. Despite high variability in resource use for similar projects, little long-term development takes place over the supply chain. A strategy to approach major customers and create long-term agreements with mutual incentives for increased efficiency in the process would be desirable. A greater effort on developing an efficient process is recommended instead of working with a new business transaction for every single project.

Manufacturing – from pre-processing to surveying and logistics

When the sales department receives an order, accumulated information from the sales process is transferred to the manufacturing section, where the work of defining a product from the given information commences, deciding manufacturing methods, scheduling the manufacturing, and ensuring that spatial on-site information is acquired. Since joinery manufacture requires tighter tolerances than construction in general, the drawings provided are not sufficient. The spatial on-site information must be verified by measuring the site on which the products are to be used and comparing the information with the supplied drawings, in order to adjust the product where necessary. This measurement on the construction site is usually performed, by the joinery products supplier.
Joinery products are manufactured using the information produced in the pre-processing and communicated mainly by 2-D drawings and a manufacturing bill. A production plan is used to show the manufacturing time required. The main support for this work is CAD software and the companies’ own routines developed to create manufacturing bills and production plans for the production staff.

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

**Observed problems**
Currently, manual methods are mainly used to acquire the necessary spatial information. These measurements are made on a 2-D basis and with a few measuring positions, which means that they do not deliver all the available and required spatial information to eliminate spatial uncertainties. The measurements involve a risk if they prove to be insufficient, inaccurate, or more time-consuming than planned for in the tender. The making of measurements on-site also requires coordination with the construction project. The time required to perform the measurements 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 submitting the tender.

In the organization studied, 1700–2000 hours are believed to be used annually for manual on-site surveying. Nevertheless the studied cases show that spatial uncertainty is one of the main contributors to waste in the joinery-product supplier process. The actual cost effect in the overall process of the spatial uncertainty to which the on-site information contributes is unknown, but it is believed to be substantial since the overall efficiency has been shown to be highly affected by problems related to remaining on-site dimensional uncertainties.

The joinery-product manufacturing units studied are small and micro sized enterprises with limited resources for process development. Much of the defining work is performed by a single person in the production pre-processing department with periods of high workload. A long unplanned absence of this role can severely affect the supplier performance. There are few routines for quality control of the pre-processing, and logical errors in design/pre-processing can pass down the value stream and not be revealed until the assembly stage. 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 components in the parcels is not always satisfactory and if the assembly instructions are also absent, this hampers the efficiency of assembly of the product. There is also poor control of the transport from the production unit to the construction site with regards to delivery time and allocation of resources for unloading.
Assembly planning – order to assembly

The main task of assembly planning is to coordinate the tact time of the production with the demands of the procurer. This function also participates in the quotation process, where the cost for the assembly work is estimated. The supplier works on national and, to some extent, international markets, which means that the projects are geographically spread. The normal strategy is to contract an assembly contractor close to the construction site. During the assembly, it is the responsibility of the contractor to support the assembly work and to deal with any 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 is such that it will be completed within the contracted time. Interaction with the on-site construction process have shown limitations and installed and assembled joinery products have sometimes needed to be dismantled to allow finishing work related to the construction process.

Assembly on-site

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

On the construction site, the assembly contractor receives deliveries from the manufacturing unit, and 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 the work with other on-site contractors, and this is usually done ad-hoc.

Observed problems
The local assembly contractors are not necessarily familiar with the joinery 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 relied upon. The development of a detailed understanding of the assembly work usually starts when the components arrive at the construction site, and this requires some time. 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.
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The arrival of component is not coordinated with the assembly needs, but rather with the time of manufacture, thus components are pushed to the construction site, causing a need for inventory buffers at the construction site. The logistics from manufacture to assembly were not controlled in the supply chain studied. 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 weaknesses in the design, timing, and information provided with the parcels of joinery components reduce 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, but much of the assembly method still 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 to do it is often limited. Only the start and the desired stop dates are known and coordination with other contractors is thus hampered. These conditions contribute to a low predictability of the assembly work and disturbance to the craftsmen who need to coordinate their own work.
3.3 CMM 3-D sensing

In this study 3-D sensing of on-site dimensions with the Proliner, a portable wire-based coordinate-measuring machine, has been tested. The performance of the machine has been evaluated with respect to its accuracy and usability in providing reliable construction site dimensions in 3-D to a level where joinery products can be fitted in the digital domain at the time of manufacture. The CMM (Figure 5) registers the position of a measurement probe as coordinates in a Cartesian coordinate system. The measurement probe is connected to the machine with a wire extracted from a measurement arm that can rotate in both horizontal and vertical directions, and uses three sensors to determine the measurement position; one measures the distance of the extracted wire and the other two measure the horizontal and vertical positions of the measurement arm. Coordinates are recorded with the measurement probe positioned to an object, and the user operates a remote control to order the machine to record that position.

Figure 5. The tested portable wire-based coordinate-measuring machine with its wire-connected measurement probe with a 7 m range. The measurement arm has ranges for horizontal and vertical rotation of 402° and 104°, respectively.

CMM Accuracy

The CMM precision was tested by measuring the scatter when 30 observations were made at each of four locations in a fully randomized design, using four reference targets that fix the measurement probe during the observations. The centre of gravity of the cluster of points at each position is the “mean” value from which the random error was calculated.

A 3-D scatterplot for each of the CMMs three sensors shows how the measurement results are scattered around the centre of gravity. For the wire-extraction sensor positions, the measurement uncertainty is unequal in the three directions, with the largest 95% confidence limit of the scatter, ± 1.9 mm, in the
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Z-direction with 650 cm wire extracted (Figure 6A). For the horizontal sensor positions, the inequality concerns only one direction, the Z-direction, where the 95% confidence limit of the scatter is ± 0.5 mm, significantly less than the ± 0.8 – 0.9 mm, for the X- and Y-directions (Figure 6B), and for the vertical sensor, the 95% confidence limit of the scatter is small, ± 0.1 - 0.2 mm, in all three directions (Figure 6C). Note that the X-, Y-, and Z-directions cannot be compared between the tested sensors owing to different Cartesian orientations in the setup.

Figure 6. Scatter-plots of the three portable wire-based coordinate measuring machine sensors show the distribution of deviations in the XYZ directions. The three different colours are from different test positions. (a) Scatter of the wire-extraction sensor measurements, (b) Scatter of the horizontal sensor measurements, and (c) Scatter of the vertical sensor measurements.

One-way analysis of variance (ANOVA) of the measurement data testing the CMM sensor precision shows that the distance from the CMM to the measuring position, the amount of extracted wire, is the greatest source of variation in the CMM random error. This is reflected in the confidence interval plots (Figure 7), showing the magnitude of the uncertainty associated with the mean of each set of CMM measurements depending on the sensor positions.

The wire extraction sensor gives an uncertainty with 95% confidence of 0.27– 0.35 mm at the 100-cm position, and of 0.78–1.13 mm at the 650-cm position, (Figure 7A). The horizontal and vertical position sensors show a more constant contribution to the measurement error along their working range (Figure 7B and 7C). Note that the measurements for the horizontal and vertical sensors use different wire extraction lengths, which explains the difference between them in the size of the mean error.
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Tests of the Leap functionality of the CMM with a series of nine leaps show that the measured individual cumulative errors for each of the leaps are significantly greater than the user information provided with the machine (Figure 8A and 8B). These mismatch errors have irregular orientations. As the leap series continues, the measured absolute error vastly exceeds the cumulative mismatch error (Figure 8C and 8D). Here, the absolute uncertainty reaches values of hundreds of millimetres, and the absolute uncertainty can change directions (Figure 8C). The directions of the Leap errors are irregular and are therefore difficult to predict and compensate for.
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Figure 8. Mismatch introduced using the CMM leap function. (A and B) Measured individual mismatch versus machine mismatch information for the two test runs (green and red bars vs. blue bars): (C and D) Measured absolute mismatch (red line) versus accumulated measured individual mismatch (green and blue lines) and accumulated individual mismatch information given from the CMM (pink line). Absolute mismatch = measured deviation between wall reference and the laser projection line in the experimental setup (Paper IV).

Four cases have been studied to understand the CMM 3-D sensing in practice. These have shown in a number of examples that the accuracy is far less than that shown in the CMM accuracy testing and in product specifications.

In one example, the processed measurement model of the conference room showed uncertainties that became evident when the corners and the way in which the measured surfaces met each other were studied. At the six corner points, there were mismatches of 0.43 mm, 1.46 mm, 2.36 mm, 3.44 mm, 5.54 mm and 8.68 mm (Figure 9).
Another example of the accuracy problem was seen in a 12-storey staircase, where a number of uncertainties were revealed when the measurement data were processed to give a 3-D model. One uncertainty was found in small angular deviations of surface planes that could easily be thought reliable. These were recurring problems affecting the measured floor heights and staircase contour size. A comparison between floor height measurements made with the CMM model and with a steel tape show differences in heights specified in the architectural drawings, as well as mutual differences of several millimetres and even centimetres (Figure 10). These uncertainties are far from being of a size on a par with joinery product tolerances.
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Figure 10. CMM and steel tape measurements of floor heights compared to drawings.

These and other case experiences have shown measurement errors of considerably greater magnitude than the test of the CMM sensor accuracy reports. Four factors have been identified that affect the measurement accuracy in the studied cases:

- Accuracy of the measured coordinates
- Representativity of the chosen coordinate positions
- Error leveraging
- Leap Function

Since all these factors are involved in the CMM 3-D sensing, measurement errors significantly greater than the tolerances of joinery products have arisen in the studied cases. Taking into consideration the difficulties in estimating the size and direction of errors, the reliability of the CMM-based models is not on a par with joinery-product tolerances. Hence, the hypothesis that dimensional uncertainties of as-built construction sites can be reduced to a level on a par with joinery-product tolerances is rejected.
The four cases led to a number of usability problems with the CMM measuring equipment. From a usability perspective, four main usability problems have been experienced in the studied cases:

- Range and reach
- Limitations in “picturing” the construction site and its details
- Level of expertise needed to perform reliable measurements
- Difficulty in processing measurement data to measurable 3-D models

Range was an issue in all the cases and the Leap functionality was a feature that introduced severe uncertainties and errors. Due to the frequent presence of obstacles on construction sites, problems where the wire connected CMM measurement probe could not reach around obstacles were common. To be beneficial when supplying joinery products, the 3-D sensing needs to cover more than a single site detail and experience showed practical difficulties with the CMM site picturing. The CMM site measurement required a high level of expertise to yield a reasonable site picturing, avoiding range and reach problems, observing possible errors that are very small in relation to the measured object, and correctly considering the offset of the measurement probe in all situations. Due to these difficulties in the on-site measurement, the processing of the measurement data into 3-D models also requires a high level of expertise and, considering the complexity of the on-site measurement the off-site data processing can hardly be performed by someone other than the person performing the on-site CMM 3-D sensing. Performing the data processing on-site is also difficult, due to the time needed and the large screen necessary for this work.
3.4 Laser scanning 3-D sensing

3-D sensing of as-built dimensions with laser scanning technology has been tested in one case. A Leica Scan Station C10 machine was provided by a laser scanning service provider who also performed the scanning in the presence of the author of this thesis, and provided a finished 3-D model and the raw laser scan point-cloud data. The 3-D model and the point cloud were used by the author to qualitatively compare the 3-D model with the information available in the point-cloud data, and to study the shape and level of detail provided by the 3-D model and the point-cloud data. The point cloud was subjected to a qualitative study with respect to coordinate density in different regions of the point cloud and with different angles between the laser beam and the captured geometry, noise depth, identification of detail and detail boundaries, etc. Surface irregularities were studied using deviation maps where the point cloud data were compared with best-fit planes and surfaces. As with the CMM, the performance was evaluated with respect to its accuracy and usability in providing reliable as-built construction site dimensions in 3-D to a level where product-to-room fitting of joinery products can be performed factory in the digital domain.

The results show that laser scanning captures many details of a construction site with an accuracy down to a few millimetres, and topological irregularities in the on-site surfaces can be seen in the scanner point cloud data. Processing the scan information has the potential to yield a 3-D model that can be used for measurement within the model. Many of the uncertainties associated with a manual survey can be avoided or reduced, although uncertainties remain.

The point-cloud data hold no semantic information and must therefore be interpreted. To be more useful, the 3-D sensing information should be processed into a 3-D BIM model that also holds semantic data. Current research has shown that this scan-to-BIM process can be carried out automatically, although it is currently usually a manual operation that is both labour-intensive and error-prone (Xiong et al., 2013). In the scan-to-BIM processing, details in the point cloud need to be selected to represent a given model object. This can be challenging due to difficulties in identifying borderlines in the seemingly detailed information captured on-site. Examples of these difficulties are shown in Figure 11 for details such as skirting boards, cable channels, window trimmings and ledges, etc.
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Figure 11. Examples of borderline problems. (a) Zoomed-out details. (b) Zoomed-in detail showing a lack of coordinate density. The white areas on the upper surfaces of the window ledge and the cable channel below the window are difficult to distinguish from each other. (c) Zoomed-in corner shows blurriness of surface boundaries.

A comparison of the point-cloud-based 3-D model from the professional service provider with the original point-cloud data reveals that details are missing in the 3-D model, for example skirting boards and cable channels (Figure 12a–Figure 12b), and the point-cloud intersects wall surfaces of the 3-D model (Figure 12c). This indicates that the 3-D model does not consider the actual inclination of the on-site wall.

Figure 12. (a) A skirting board present in the point cloud is missing in the 3-D model. (b) A cable channel present in the point cloud is missing in the 3-D model. (c) Intersecting wall surfaces.

Further investigation of the inclination of the wall in the 3-D model reveals local discrepancies of up to 22 mm between the laser scan point cloud and the 3-D model of the curved wall processed by the professional service provider (Figure 13a). This indicates problems in fitting non-regular surface topologies. This is a region with difficulties that is also reported in the literature, where most point-cloud processing assumes flat surfaces or shape primitives against which the point cloud data are fitted, and topological surface deviations are not detected (Xiong et al., 2013; Anil et al., 2013; Bosché & Guenet, 2014). A best-fit approach to the point-cloud data representing the curved wall gave a reconstruction of the curved wall surface with a much better fit (Figure 13b).
Figure 13. An isometric view of a curved wall section with a skirting board. (a) A comparison between the 3-D model and laser scan point cloud show a deviation of approx. 22 millimetres. (b) A best-fit surface (black) show better fit to point-cloud than the 3-D model.

Topological surface irregularities frequently occur in on-site surfaces. This is information that can be detected in the point-cloud data. This is exemplified in an analysis of floor and wall point-cloud data using best-fit planes and colour-coded deviation maps identifying topological surface irregularities (Figure 14a, Figure 14b). These show topological surface irregularities ca. ±12 mm in size on the floor surface (Figure 14a), and ca. ±13 mm in size on the wall surface (Figure 14b).

Figure 14. Color-coded deviation maps between the point cloud and best-fit planes showing the deviation in millimetres. (a) Floor surface irregularities of −14.5 / + 9.6 millimetres. (b) Wall surface irregularities of −12.8 / + 13.2 millimetres of an assumed planar wall.

These results show that laser-scanning 3-D sensing has the potential to capture most of the relevant details needed for a joinery-product producer, but the challenge is to retain the information through the scan-to-BIM processing. The frequent presence on-site of topological surface irregularities combined with point-cloud noise depth and point-cloud density variations makes it difficult to achieve measurement accuracy on a par with the accepted tolerance of joinery
products. It is therefore uncertain whether the performance of current laser-scanning 3-D technology can make possible product-to-room fitting of joinery products in the digital domain at the time of manufacture.

3.5 Enterprise size and industry performance

Recent European and Swedish industry performance has been assessed on the basis of business statistics data from Eurostat and Statistics Sweden using the NACE-Rev. 2 classification of economic activities in the European Union. This assessment shows how the size of the company affects the firm performance and how that can relate to the business structure of joinery-product suppliers. Structural business statistics show that the most of Swedish enterprises are micro-sized but that the large companies employ most people, have a higher turnover and add more value (Figure 15a). At the European level (EU-27) the situation is similar, large companies have the highest value added and employ most people, but here the micro-sized enterprises are significantly better than small and medium-sized enterprises in creating value and employment (Figure 15b).

Figure 15. Business structure by enterprise size of all industry classes (a) Swedish share (%) of enterprises, employment, turnover and value added by size class (Poldahl, Wikstedt, & Åhman, 2010). (b) EU-27 share (%) of value added and employment for the non-financial business economy (Eurostat, 2015c).

Figure 16 present a selection of Swedish enterprise classes related to products provided by joinery-product suppliers, to provide an overview of the organisational structure of the Swedish wood products manufacturing industry. This selection of enterprises shows a size structure with a significant share of micro and small enterprises in a diversified range of products (Figure 16). The manufacture of other builder’s carpentry and joinery industry class (NACE 16.239), which includes joinery-product suppliers, shows the most pronounced micro and small enterprise profile. This includes the largest share of one-man enterprises, and the number of persons employed decreases with the enterprise size (Figure 16c). None of the enterprises with 200 or more employees are represented in this industry class (Figure 16b).
Figure 16. Size class distribution and employees in selected industry subclasses of Swedish wood products and furniture manufacturing enterprises (Statistics Sweden, 2013c).
(a) Number of companies in different size categories based on number of employees. (b) Number of employees in micro, small, and medium sized enterprises versus the number in large size enterprises. (c) Number of employees in different company size classes and in different industry categories.
The manufacture of products of wood and furniture are the major contributors to the production value generated in the European wood-working industry (Figure 17a). Joinery products are represented in both these industry groups, although in the business statistics they are represented only in the industry class “Manufacture of other builders carpentry and joinery” (NACE 16.23) and they contribute to 19% of the wood-working industry production value (Figure 17b.)

The four EU-27 industry sectors, manufacturing, construction, manufacture of wood and products of wood, and manufacture of furniture, show divergences in size-structure-related performance in terms of value added, persons employed, and apparent labour productivity (Figure 18).

In the manufacturing sector, large enterprises have a dominant position in all three performances, with 55.5% of the sector value added, 40.0% of work force, and apparent labour productivity of EUR 52.8 thousand per person employed, some EUR 8.0 thousand more than the non-financial business economy average (Figure 18a). Overall, the manufacturing sector performs well in most aspects in comparison with non-financial business economy, except for the profitability measured as gross operating rate (Figure 19)
The construction sector that is a major consumer of joinery products shows an enterprise size structure in which micro and small enterprises contribute the most to the value added and number of persons employed (Figure 18b). This is in contrast to the manufacturing sector (Figure 18a), and to the non-financial business economy as a whole. The areas of the bubbles show that the apparent labour productivity is lower in the smaller enterprises and, since these contribute the most to the production value and persons employed, this affects the total productivity of the industry section negatively (Figure 19).

In 2010, the EU-27 construction sector accounted for 15.1% of all the enterprises in the non-financial business economy, employed 10.1% of its work force, and generated 8.4% of its value added. The construction sector can be characterised as having enterprises that are, on average, smaller than the non-financial business economy average, in terms both of their employment levels and of their added value. The share of personnel costs in operating expenditure was 23.9%, i.e. greater than the non-financial business economy average of 16.4%, which exemplifies the importance of labour input in the construction activity as a whole. The apparent labour productivity was EUR 37.0 thousand per person employed and the average personnel costs were EUR 31.4 thousand per
employee. The apparent labour productivity was EUR 7.8 thousand below the average for the non-financial business economy, and the average personnel costs per employee were higher (Eurostat, 2013a).

The wood and wood products manufacturing sector in EU-27 in 2010 comprised 184 thousand enterprises, employed 1.05 million persons, and generated EUR 31.2 billion of value added. This value added represents 0.5% of the non-financial business economy total and 2.0% of the manufacturing total (Eurostat, 2013c).

The wood and wood products manufacturing sector shows a size structure similar to that of the construction sector (Figure 18c), where small enterprises contribute the most to the value added and the second most to persons employed after the micro enterprises. The lower apparent labour productivity in these two categories lowers the performance of the entire sector (Figure 19). The apparent labour productivity of EUR 30.0 thousand per person employed was one of the lowest levels of apparent labour productivity among the manufacturing NACE divisions, EUR 14.8 thousand lower than the non-financial business economy average, and EUR 22.8 thousand lower than the manufacturing average. Despite low productivity, the profitability measured by the gross operating rate was 9.1% which is only slightly lower than the non-financial business economy average of 10.1%, and marginally higher than the manufacturing average of 9.0% (Eurostat, 2013c).

For the Swedish manufacturers of wooden doors, windows, and other builders’ carpentry and joinery, large enterprises contribute the most to the value added (Figure 20). The productivity, measured as value added per employee, is similar for large medium and small enterprises, but lower for micro and one-man enterprises. This situation is somewhat different from that in European
manufacturing (NACE 16), where productivity is significantly higher in the larger companies (Figure 18a), and is evidence of lower levels of industrialisation within the Swedish manufacturers of wooden products.

![Figure 20. Value added and value added/employee in 2013, in Swedish manufacture of wooden doors, windows and other builders’ carpentry and joinery, and Swedish manufacture of office shop furniture, furniture and fittings, kitchen furniture, and other furniture (Statistics Sweden, 2013a).](image)

The EU-27’s furniture manufacturing sector included 130 thousand enterprises in 2010 that employed 1.04 million persons. This represented 0.6% of the total enterprise population in the non-financial business economy and 0.8% of the workforce. The EUR 30 billion of value added generated was 0.5% of the non-financial business economy total (Eurostat, 2013b).

In the EU-27’s furniture manufacturing sector, small enterprises were particularly important. They contributed the most to both the value added (28.1%), and number of persons employed (27.3%), closely followed by medium and large enterprises (Figure 18d). Micro enterprises were significantly behind in their share of value added (16.4%) but in third place regarding number of persons employed (23.9%). Large enterprises lead in apparent labour productivity, closely followed by medium and small enterprises, with micro enterprises far behind. In productivity and profitability measures, the furniture sector falls behind the manufacturing, construction and manufacture of wood and wood products sectors in all aspects except for wage-adjusted labour productivity, where the construction sector is beaten (Figure 19). The wage-adjusted labour productivity ratio at 120.0% was the second lowest among the manufacturing NACE divisions, well below the averages recorded for the non-financial business economy (144.8%) and manufacturing (148.0%). The operating profitability, as measured by the gross operating rate, was at 7.9% also below the manufacturing average (9.0%) and the non-financial business economy average (10.1%).

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In the Swedish furniture industry, the manufacturer classes shown in Figure 20 show a size structure in terms of value added that is different from that of the general European furniture industry. In Sweden, medium enterprises contribute the most to the value added, and the productivity measured as value added per employee is similar for large, small, and micro enterprises, while peaking for the medium enterprises and dropping radically in one-man enterprises. This is evidence that the larger Swedish enterprises have not been able to increase the level of industrialisation and still require high levels of craft work.
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4 Analysis of possible innovation

In the following sections, the experience from the work with the appended papers are discussed from an innovation perspective, using the problems identified as an aid in focusing the innovation efforts to increase the competitive ability in supplying joinery products efficiently. Lean principles have been used as an analysis perspective to identify efficiency restraints, strongly influenced by the field of Lean construction and the understanding that information management is crucial in the fragmented nature of the construction industry that is the major consumer of joinery products.

Joseph Schumpeter is seen as the father of innovation research, who argued (1934) that anyone seeking profits must innovate, and described development as a historical process of structural changes, substantially driven by innovation. His definition of innovation implies that innovation has a wide perspective on change, not just on a product but also on methods, markets, supply, and industrial structure. An innovation is an idea, practice, or object perceived as being new by an individual or other unit of adoption (Rogers, 2003). An innovation can therefore be using an innovation from one field to another to achieve competitive changes in a product, process, market, supply, and/or industrial structure. Innovation is therefore an essential driver of competitiveness.

A peculiarity in the supply joinery products is the need to know the as-built on-site spatial dimensions before the products are manufactured in order to reduce the uncertainties associated with product-to-room fitting when pre-fabricated products are delivered to the site. The studies have shown that current methods for acquiring the as-built spatial data are not sufficient to eliminate spatial uncertainties. Much of the waste in the joinery-product supplier process, identified through lean principles, is due to these uncertainties and this severely affects the supplier efficiency. The ability to eliminate spatial uncertainties from the as-built on-site environment is therefore an important innovative factor in the process of supplying joinery products. This was the reason for investigating 3-D sensing technology as a possibly viable tool to eliminate spatial uncertainties from the as-built on-site environment.

4.1.1 Removal of waste, a process innovation

The identification of waste not only shows the need for innovation but it is also an indicator of where to focus the innovation efforts. The studies in Papers I and II show that time and effort that do not add value are put into the process of supplying joinery products to construction.

The concept of value in Lean is a well-explored topic in the research literature. In brief, the focus should be on maximizing the value for the end user; however, in supplying joinery products to construction the manufacturer is not in direct contact with the end user. The joinery products supplier is usually procured by the construction contractor and this affects the definition of the value, and the
The architect, who often prescribes a general design of the product to reflect what the client values, also has an agenda regarding what adds value to the joinery product. The maximization of the value for stakeholders in this value-chain is not considered here, but 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 on the effectiveness or efficacy of the process. Effectiveness/efficacy is doing the right things, the management of the project, whereas the efficiency is concerned with doing things right, the logistics in the project, the work flow (Fearne & Fowler, 2006; Drucker, 2007). An effective process thus ensures that the intended result is achieved and that the process is run efficiently if no time and effort are wasted. This can also be related to Lean principles and the waste definition used in the Lean literature (Womack & Jones, 2003; Liker, 2004).

Problems in this process have been identified based on the definition of waste according to the seven wastes of Lean (Womack & Jones, 2003). In Paper II, this is highlighted using the TIMWOUD acronym, which is a variant of the TIMWOOD acronym that is used to describe the wastes of Transport, Inventory, Motion, Waiting, Over-production, Over-processing, and Defects. The TIMWOUD variant refers to under-processing instead of over-processing and reflects the experience of the cases studied.

In Paper II, all seven types of waste in the TIMWOUD acronym were found. Therefore the potential for improving the efficiency by eliminating waste from the process is substantial (Figure 21). In construction, the percentage of the total hours which adds value has been reported to be 13% (Strandberg & Josephson, 2005; Björkman, Josephson, & Kling, 2010). The amount of waste found in Paper II suggests a situation similar to that reported elsewhere in the construction industry. Here, the importance of identifying the root cause of the waste at a cross-organizational level is highlighted. Lean principles are suggested as providing guidance for this work.
An examination of the case experiences against Liker’s 14 management principles (2004), show important violations of these principles. 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 to develop 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 — there is limited focus on developing mutual processes, skills, and finding the best practice within the internal supply chain and between industry colleagues and/or project partners. Networking on these topics between industry colleagues and project partners can provide useful insight as well developing the people involved;

4) Continuously solving the root-cause of 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 repeatedly re-occur.
These four principle areas are recommended as guidance for a cultural innovation to strive for in the supplying of joinery products. This will help in learning to see waste in the process, the elimination of which can be used for innovation in the supplier process.

**4.1.2 Effects of short-term contractual relations**

An effect of the short-term contractual relations found in Papers I and II is that much work and time was spent on the business transaction and this constrains the value adding process.

Paper I considers the time between the business transaction and the time when value is added to joinery-product, and Figure 22 shows that of the 81% of the calendar time (week 87-183) is used for the business transaction, from the preliminary inquiry until the order is received, and during this time no value is added to the joinery product. Most of this time, work such as that for the quotation and prescribing documents, is waiting for value-adding activities. Thereafter 19% of the calendar time (23 weeks) is used to engineer, manufacture, transport, and assemble the joinery products on the construction site. This time is at the very end of the construction project and puts high pressure on the supplier to finish the task within the stipulated time frames.

The time delay for the processed work limits the interaction between the supplier and the architect, whose prescriptions are to be defined in 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’s need, a vision that the joinery products supplier is to realise into a product. The time delay also reduces the possibility of levelling out the workload in the supplier process. A great variability in workload was found in Paper I and this caused great stress in the production pre-processing and manufacturing, which affects the quality of this work with effects down the value stream.

Paper II considered the effect of this skewed distribution of activities during the project time, and showed an under-processing of the product definition and of the planning and coordination stages. This means that problems pass down the value stream and have to be solved at a late stage in the supply process. This made the supply process more unpredictable and less efficient. Further, time delays were seen to obviate major gains in applying concurrent engineering methods to the value stream.

It was argued that production pre-processing is central to the supplying of joinery products; it is where the architectural ideas are formulated into products and where assembly methods are created. It is evident that it is important to improve integration and information exchange between the architect, production pre-processing, and assembly in the product determination.
In the Lean construction literature, relational forms of contracting are advocated, and the necessity for procurement at the project level is questioned (Forbes & Ahmed, 2011). This would support long-term procurement relations, with more focus on adding value and less focus on the business transaction. This is an innovation of the joinery-products supplier process that is encouraged in this thesis, since the potential for waste reduction is substantial. With longer contractual relations, the focus on the business transaction can be transferred focus more focus on concurrent engineering and a closer interaction between those who create value in the supply process. Since no pause in the value adding work is needed for the business processing, the supplier time horizon is increased and this stimulates interaction with prescribers, enhanced production and assembly planning and product engineering, and it makes possible increased levels of prefabrication of the joinery-products. This would result in a more efficient transfer and accumulation of knowledge along the value stream, as information becomes more transparent and is mutually developed. Much of the current under-processing could then be avoided, and the flow of the on-site work would increase and thus reduce the time needed on the construction site.

4.1.3 Need for information management

An important measure to eliminate waste lies in the efficient management of information. In the cases studied in this work, 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 build-up of knowledge 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 in Figure 23. This project involved the supplying 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. Mainly on-site actors were connected to this information platform and the joinery product supplier was neither aware of nor connected to this platform. The connection of the joinery product supplier to the information platform was simply overlooked by the client, who had no intention of restricting information access.

As a result of this disconnection from information, the joinery product supplier was not aware of the 3-D model already created by the architects and they made one of their own, which contained errors. This resulted in erroneous product components being manufactured and transported to the construction site, and it affected the assembly work as well. In this case, the necessary information was not made available to the supplier.

Paper I discuss in greater detail the situation where a business transaction is based on incomplete information. The information from the prescribing part is seldom fully defined; details are omitted and left for the supplier to solve. When the joinery product is priced, the estimate is based on the available information and, since this work is not chargeable, the resolution of the estimate in the quotation tends to be limited, so that the project involves a risk in profitability. When the order is received and production pre-processing personnel are engineering the
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product, interaction with the prescribing part would be appropriate, but this seems not to be the normal routine since this is believed to prolong 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 joinery product supply chain, where 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 arise late in the process, when the product is being assembled and fitted on the construction site. The following were 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 the 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, and this requires planning and coordination when working in a cross-organizational manner. It was evident that the tact of the assembly work is not defined and that the arrival of the joinery components is not coordinated with the need for them in the assembly, so that the concept of just-in-time is not used and the components were stored at the construction site, which causes more transport of materials and more motion for the workers. Furthermore, the risk of damage to the components increases when they are exposed to the environment on the construction 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 (Cohen, 2007; Forbes & Ahmed, 2011), and Line of Balance and 4D/nD information modelling (Björnfot & Jongeling, 2007) seem to be potential innovations to help solve the problems in the area of planning and coordination. Much of the information management methods suggested in construction can benefit from 3-D/BIM modelling, as it serves as a base from which information can be organized and visualized (Akinci et al., 2006; Anil et al., 2013; Ding, Zhou, & Akinci, 2014; Bosché et al., 2014). Further efforts in 3-D/BIM modelling are therefore a suggested innovation to solve the problems of knowledge and information mediation.

4.1.4 Approaching concurrent engineering

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

Paper I and Paper II both show the need for increased integration between the value-adding actors. In Paper II, the current process is compared with a process adopting principles of concurrent engineering (Figure 24), and 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 drop in knowledge in each downstream handover.

![Figure 24: A future state with a concurrent engineering approach show the potential for increased knowledge transfer and shorter lead time compared to the current process.](image)

In the studied cases, production pre-processing is central; because this 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 a mutual understanding of how decisions affect the process and the product. For example, it can be useful in the architectural determination to take advantage of the supplier product competence in order to enhance product quality and process efficiency.

In Paper I, it was pointed out that prescribers, such as architects and engineers in construction, deliberately leave gaps in the suggested product for the supplier to solve, based on the assumption that the supplier are more of an expert than the prescribing part. However, the supplier thinks that they are supplying a product according to the prescribing documents. This gap in information and perception
of reality could be avoided if the supplier and prescribing party could 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 described in Papers I and II.

To take the full advantage of the potential of concurrent engineering principles, the supplier must be able to interact with the prescribers when they prepare the prescribing documents. Currently this is restrained by the nature of the contractual relations, and innovations in the joinery-product supplier process through concurrent engineering would require a new type of contractual relation.

4.1.5 Planning and coordination
In the cases studied, much attention has been given to the business transaction and the design information. Planning, coordination, control, and assembly information have been given less attention. Efficient management of the interaction between activities, the combined effects of dependence and variation, is essential if projects are to be delivered in the shortest time (Howell, 1999). The Lean approach is therefore to avoid variation in work flow through planning and control, where “planning” means defining criteria for success and producing strategies for achieving objectives and “control” means causing events to conform to plan and triggering learning and re-planning. Therefore added planning and control to the joinery-product supply process can increase the predictability and hence project performance. This planning and coordination is needed at several levels.

In Paper I, it was shown that in the quotation, the planning of a specific production method in terms of time and resource allocation. However, when starting to manufacture the products, it was found that the planned production method was not feasible and that additional resources were needed in the production process, i.e. the planning in the quotation work was insufficient and added uncertainty to the project. Here, “uncertainty” is the difference between the information needed and the information already possessed (Galbraith, 1973). To reduce uncertainty, information must be acquired as the project progresses (Winch, 2003). Thus work that might not be considered in the quotation needs to be performed to reduce uncertainty.

In Paper II, a number of problems which arose during the assembly were due to deficiencies in planning and coordination. It was found that the tact for the assembly works mainly at a start and stop level. The exact details and available time for each phase are usually unknown, which means that there are uncertainties in this process that decrease the predictability of the work to be planned. Furthermore, it was seen that coordination is needed with other contractors on-site during the assembly, and this coordination is left to the assembly contractor to manage as the need arises. This causes frequent changes in
the work at hand and adds motions and waiting time to the process and this affects the predictability and efficiency of the assembly work. The frequent change in the work at hand is a typical effect of insufficient planning and it has been shown to reduce the time for value-adding work (Strandberg & Josephson, 2005). Further, the lack of planning for the transport of the joinery-product components from the manufacturing to the assembly site caused disturbances and resource waste in the assembly work, together with a risk of physical damage to the one-of-a-kind products.

In Paper V, it was shown that there is a need for the joinery-products supplier to survey a construction site to verify the spatial information given before the joinery production starts. Since the adjacent surroundings for the joinery product do not exist when the supplier needs to perform this surveying, the survey needs to be coordinated with the construction contractor. The best solution is therefore to plan and coordinate the surveying with the construction work early in the supplier process to avoid this situation.

From that is discussed above and presented in the appended papers, an increased level of planning and coordination is an important measure if greater efficiency is to be achieved in the supplying of joinery products. In this context, the use of tools that enhance an understanding of the process and which lead to an increased visualisation, e.g., using line of balance and 4D modelling, could be investigated. To decrease the time for assembly on-site, more planning, coordination and control is suggested. To achieve this, it is suggested that the roles for production pre-processing and assembly planning are to be changed.

4.1.6 Innovation through 3-D sensing and BIM modelling
The need for surveying the as-built on-site environment is a special characteristic of supplying joinery products. The supplier performs this surveying to avoid manufacturing products that will not fit in the intended environment, as it is not uncommon for there to be differences between the as-planned and the as-built construction site environment. The surveying is usually performed by the supplier but occasionally by their client. This is important since the reliability of the surveying is essential and there is a responsibility and therefore a risk in providing this information. This is the reason why the responsibility is often given to the supplier.

As shown in Papers II, III, and V, there are limitations in the currently used manual surveying methods which affect the level of prefabrication and the amount of waste in the supplying process. Increased prefabrication and reduction of waste are probable outcomes of adopting a 3-D sensing technology that can reduce on-site dimensional uncertainties to levels on a par with joinery product tolerances, but a further reduction of waste requires increased integration to the construction process and to achieve this further efforts in BIM are a plausible strategy. With a combination of these technologies as-built BIMs can acquire the
information needed for increased automation and prefabrication, and this will give a substantial reduction in waste through better integration with the construction process. Three examples of how such BIMs can develop the supplier process were given in Paper V: 1) moving the manual fitting at the end of the supply process to the digital environment early in the supply process, to allow automated product-to-room fitting, and the use of numerically controlled machinery to perform the physical fitting of the product components; 2) adapted to the size limitations of transport routes on-site, the parcels can be designed in the digital domain to optimize on-site delivery. 3) synchronizing the supply process with the construction process by ensuring that the adjacent environment has been prepared for the assembly of the joinery products.

As seen in Papers IV and V, 3-D sensing technology to meet the accuracy and usability demands for the supplying of joinery products is not yet readily available. Few efforts are being made to pursue high accuracy 3-D sensing on large objects and model generation of the scan data that can be used for product-to-room fitting during design. Paper V shows how the scan-to-model process itself has a number of pitfalls in maintaining accuracy from the 3-D sensing data. This is therefore a field of research with which joinery-product suppliers should keep in touch in order to take advantage of the innovation possibilities within the supplier process that the adoption of 3-D sensing and BIM technology can provide.

The adoption of 3-D sensing technology is a possible task for the joinery-product supplier guild, but there are two obstacles in pursuing such efforts: 1) current 3-D sensing technology needs to be developed to meet the accuracy requirements for creating benefits in the supplying of joinery products, and 2) the organisational structure and available competence within the joinery-product supplier guild are probably limitations when carrying out the adoption and technology development needed. It would be better to adopt 3-D sensing technology in cooperation with other guilds within the construction industry that can benefit from more reliable as-built spatial information.

It is more difficult for the joinery-product suppliers to take the lead in developing BIM since much of the information in the BIM will come from other stages of the construction value chain. However, the adoption of this methodology is a recommended innovation, where 3-D sensing can provide the BIM with as-built instead of as-planned geometries. The 3-D model is an information carrier to which much metadata can be connected in a BIM that is otherwise difficult to communicate as efficiently. Here the focus should be on integration and planning towards the construction process, together with the creation of reliable as-built 3-D data. The joinery-product supplier can gain considerable benefit from information that can be carried with a BIM, but it is dependent on the increased implementation of BIM within the construction industry and their adoption of this methodology themselves.
4.1.7 Need for organisational innovation

The work described in this thesis has been pursued in order to apply modern methods and technology to the supplying of joinery products. Lean-production principles and 3-D sensing technology have been chosen as tools in exploring possible process innovation and increased industrialisation. As experience has been gained and increased through the case studies and theoretical studies, the question is: who will drive the methodological and technological development in this industry sector? Is the organisational structure hampering the process innovation rate? How efficient is the business structure of the joinery-product suppliers?

From a process efficiency perspective and considering possible areas of innovation, the business structure has been claimed to affect the productivity and level of innovation, since the probability of being able to engage in research and development increases with increasing size of the firm (Schumpeter, 1934; Audretsch & Acs, 1991; Crepon, Duguet, & Mairesse, 1998). The engineer-to-order joinery-product supplier is the term chosen in this thesis to describe the joinery-product supplier that is industrially categorised in the manufacturer of other builder’s carpentry and joinery industry sub class, NACE 16.239. They are most often one-man, micro, or small enterprises, according the EU SME definition.

The enterprise size and industry performance outlook show that, with an industry structure where micro and small enterprises contribute the most to the value added, the productivity is probably lower than in the non-financial economy in general. This is the situation which applies in the manufacture of wood products and also within construction, which is the main customer of wood products, both showing below average productivity performance.

In construction, much of the production is performed close to the customer, on-site, due to the limited presence of prefabricated products that can be manufactured industrially off-site. This has restrained much of the competition since both customer and supplier are localized in the same geographical area. Due to the limited geographical market, the number of potential customers is small and this limits the possibility of investing in industrial facilities and of developing industrial methods and processes. Large construction enterprises often have representation in many geographical areas, and in these regions they perform much like any other regional competitor. These are factors contributing to the fact that the level of manually performed work is still higher in the construction than in the manufacturing industry.

As a supplier to the construction industry, the manufacturer of wood products needs to integrate with the construction process (Paper I). The joinery-product supplier often has the responsibility of assembling the products on-site, and it can be assumed that among the joinery-product suppliers, the smaller the enterprise
the lower is the level of automated work performed, with a high proportion of on-site work instead of more industrialised off-site work.

The experiences recorded in Papers I, II and V show that the joinery-product suppliers have not been able to fully utilize industrialized processes in terms of cost efficiency, innovation, and production methods, despite their off-site manufacturing. Here, integration with the construction industry is one area that can be approached with more industrialized methods. Finding new approaches requires new thinking and prioritizing of innovation. This is a challenge in micro and small organisations with a large proportion of manual working methods and a high focus on short-term challenges. There are few resources and little competence available for strategic and innovation work. An organisational innovation is therefore suggested, performing some form of organisational consolidation where benefits of scale can be utilized to achieve resources and competence working with process, methods, technological, and business innovation to increase the industry performance.

This is in line with the report of Brege et al. (2001) who studied strategic groups within the Swedish furniture industry, were joinery-product suppliers where represented as one of the strategic groups. It was reported that the sector has a high share of small enterprises where 10% of the enterprises are responsible for 60% of the sectors turnover, and the strategic groups that utilize an economy of scale are the most profitable. The suggested strategy for the groups with a distinct micro and small enterprise profile and low profitability is to achieve an organisational consolidation or to further specialize on a niche to decrease competition. A reflection on the latter is that the narrower the niche the larger must the geographic market be to find an appropriate number of customers. This is difficult for the furniture enterprises, according to Brege et al. (2001) since they lacks control over the market channels over a wider geographical areas, a situation resembling that of many of the joinery-product suppliers.
5 Conclusions

This thesis has explored possible process innovations in the supplying of joinery products. Lean thinking and information management principles have been used to identify contributors to inefficiency and to define areas for innovation in order to improve the supplying of joinery products.

The supplying of joinery products is closely related to the construction industry, where increased levels of industrialization are being advocated. In an industrialized context, Lean operations have shown considerable success in increasing productivity. Lean principles are not merely a viable tool for identifying waste in the supplier process, but also a powerful methodology striving for perfection through continuous improvements that need to permeate the entire organisation.

In this study, the supplying of joinery products has been viewed from a Lean thinking perspective. This has revealed considerable amounts of waste along the supplier process and the need for closer interaction with the construction process. The experiences from the study lead to the conclusion that innovation in adopting Lean principles, information management, supply chain management, together with the planning and coordination of internal processes and towards the construction processes has a potential to significantly improve process efficiency.

The amount of identified waste found in the cases studied indicates that there is a significant potential for achieving greater efficiency through cross-organisational innovation focusing on:

1. Contractual relations on a longer term than at the project level, focusing more on how value can be added more efficiently, how to increase the interaction in the product and method definition, and how to improve the planning and coordination of the on-site work, rather than performing repetitive work with the business transaction that have been shown to delay the value adding-work, distancing value-adding actors from each other and hampering knowledge transfer.
2. Developing the process and cooperation along the supply chain, approaching concurrent engineering to decrease fragmentation and increasing the capacity for knowledge transfer.
3. Improved information management supporting the transfer of accumulated knowledge built up throughout the supplier process. The accumulated knowledge needs to be transparent and multi-directional, meaning that knowledge of the end process can be used early in the process when defining the product or methods for the manufacture or assembly.
4. Improved planning and coordination to support the interaction between process activities and their performers and to decrease process variation, as
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the combined effect of dependence and variation is essential if projects are to be delivered in the shortest possible time.

5. Developing competence and skill within 3-D sensing and BIM modelling, since accurate true as-built construction site dimensions are needed for the joinery-product supplier, and the 3-D model serves as an excellent information holder that can increase the visualization of information and improve the information management.

6. Methods for organisational consolidation to achieve organisational power where more resources and competence can focus on process, methodological, technological and business innovation to increase enterprise and improve industry performance.

An idea of process innovation that was an initiator of this work was the use of 3-D sensing technology to achieve a model-based joinery production. This conceptual idea has been shown to have a potential to greatly improve process efficiency, since the as-built 3-D model can function as the base for a building-information-model (BIM). BIM-driven innovation has the potential to greatly improve the process efficiency of the joinery-product supplier, and would serve as a catalyst for more industrialized processes. Three examples of as-built BIM-driven innovation possible in the joinery-products supplier process that have been identified are:

1. Moving the manual fitting at the end of the supply process to the digital environment early in the supply process. This would allow automated product-to-room fitting, and the use of numerically controlled machinery to perform the physical fitting of the product components. This has the potential of greatly reducing the time and resources needed for the on-site assembly work, since the level of prefabrication would be increased.

2. The component parcels can be designe in the digital domain during design, so that the optimum parcel size and weight taking into consideration limitations of transport methods and in-transport routes at the construction site are known before manufacture.

3. Synchronizing the supplier process with the construction process by ensuring that the on-site surroundings have been prepared for the assembly of the joinery products and that the assembly can be performed with a minimum of disturbance to the construction process. The adoption of the principles of the Last Planner system, integrated project delivery, and Line of Balance and 4D/nD information modelling are tools for addressing the process variability caused by a lack of synchronisation between the supplier process and the construction process.

This thesis contributes to the field of the secondary processing of wood and of the supply to the construction industry by introducing the novel research field of supplying joinery products to the construction industry. The theoretical contribution is the use of Lean thinking and waste detection as a tool for defining
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Possible process innovations. The practical contribution is the advocated fields of innovation in supplying joinery products and the analysis of the total process.

In essence, it highlights the relevance of acknowledging the interaction across organizational borders between value-adding instances in the supplying of joinery products. Contractual relations can separate these value-adding instances from each other so that the knowledge transfer and build-up is inhibited, although more and more information about the product needs to be accumulated before the final realisation and assembly of the product. This 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. There are a number of interfaces where information is exchanged and, deficiencies in this knowledge exchange have a great impact on the process efficiency and product quality. This lack of information exchange repeatedly leads to problems in the process, and the culture of solving problems as they arise, means that no attention is given to identifying the root-cause of these problems. This limits organizational and inter-organizational learning through the value stream, and similar problems reoccur repeatedly.

This study is limited with regard to the number of cases and organisations studied and it cannot therefore provide a complete picture of the general situation where joinery products are supplied to construction. However, together with more research in this area, it can contribute to a theoretical generalisation. In the cases studied, the procurement model and information communication inefficiency are the main hindrances. Such problems may have alternative solutions and the prerequisites for carrying out the suggested methods and their efficiency in this context need to be proven.
6 Future research

This thesis has explored possible process innovations in the supplying of joinery products and suggested areas for such innovation. More research can be devoted to the study of the supplying of joinery products to contribute to the theoretical generalisation and to prove the efficiency of solutions in suggested areas of innovation. More research on the adoption of Lean principles and the management of information, supply chain, planning, and coordination in the context of supplying joinery products to construction is still needed, as is the development and adoption of 3-D sensing technology. An increased focus on value also puts a focus on the effectiveness of the process. Based on these thoughts some ideas for further research are:

- How to establish more long-term contractual relations between suppliers and their procurers.
- How to develop supplier process integration to the construction process.
- How to increase knowledge transfer capacity along the value chain for the joinery products, especially between the prescribing architect and the joinery-products supplier in the design phase of the construction process.
- How to develop continuous learning from the experiences and knowledge gained in completed projects for engineer-to-order suppliers.
- How to develop the applicability and effects of tools and theories on planning and coordination for small engineer-to-order suppliers to construction.
- How to achieve greater synchronisation between the supplying of joinery products and the construction process.
- How to transform BIM-modelling from as-planned to as-built.
- How to exploit BIM-modelling in the supplying of joinery products.
- How to decrease or eliminate spatial uncertainties with the use of 3-D sensing technologies.
- How to meet the tolerances required on measuring equipment for eliminating spatial uncertainties when supplying joinery products.
- How to increase the level of prefabrication by decreasing spatial uncertainties of the as-built environment.
- How to achieve organisational consolidation to add resources and competence to the joinery-product industry sector.
- How to find alternative methods for organisational consolidation that can result in more organisational power and more diversified roles within the joinery-product supplier industry.
References


Anheim, F. (2001). *Entreprenörens lärande: Drivkrafter för lärande i och mellan projekt*

Anil, E. B., Tang, P., Akinci, B., & Huber, D. (2013). Deviation analysis method for the assessment of the quality of the as-is building information models generated from point cloud data. *Automation in Construction, 35*(0), 507-516. doi:http://dx.doi.org/10.1016/j.autcon.2013.06.003


Arbulu, R., & Tommelein, I. (2002). Alternative supply-chain configurations for engineered or cataloged made-to-order components: Case study on pipe supports used in power plants. *Iglc 10,*


Ballard, G. (2000). *The last planner system of production control*


References


Ding, L., Zhou, Y., & Akinci, B. (2014). Building information modeling (BIM) application framework: The process of expanding from 3D to computable nD. *Automation in Construction, 46*(0), 82-93. doi:[http://dx.doi.org/10.1016/j.autcon.2014.04.009](http://dx.doi.org/10.1016/j.autcon.2014.04.009)


References


References


Statistics Sweden. (2013a). *Basic data enterprises according to structural business statistics by industrial classification NACE rev. 2, size class, observations and year. A*
References

Compilation based on information submitted to the business statistics survey. Unpublished manuscript.


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

Authors:
Samuel Forsman, Anders Bystedt, Micael Öhman

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

Samuel Forsman¹, Anders Bystedt² and Micael Öhman³

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

¹ M.Sc., Ph.D. Candidate, Division of Wood Technology, Luleå University of Technology, samuel.forsman@ltu.se
² Ph.D. Candidate, Division of Wood Technology, Luleå University of Technology, anders.bystedt@ltu.se
³ Ph.D., Division of Wood Technology, Luleå University of Technology, micael.ohman@ltu.se
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 interchange 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.
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.
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.

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.
Forsman et al.: Interaction in the construction process—System effects for a joinery-products supplier

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.
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.

Figure 4: Timeline of the total process

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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.

References


Rother, Mike and Shook, John (2003) *Learning to See: Value-Stream Mapping to Create Value and Eliminate Muda*. Lean Enterprise Institute, Brookline, MA.


Need for innovation in supplying engineer-to-order joinery products to construction
A case study in Sweden

Authors:
Samuel Forsman, Niclas Björngrim, Anders Bystedt, Lars Laitila, Peter Bomark, Micael Öhman

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Samuel Forsman, Niclas Björngrim, Anders Bystedt, Lars Laitila, Peter Bomark and Micael Öhman
Department of Wood Science and Technology, Division of Wood Technology, Luleå University of Technology, Skellefteå, Sweden

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 paper 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 Sweden, Construction industry, Lean production, Bespoke production, Structural timber, Joinery production, Supply chain management, Engineer-to-order, Innovation, 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 impacts on the prices of living and working environments. Schumpeter (1934) claimed that...
“Innovation changes the values onto which the system is based”. Aouad et al. (2010) defined 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 matured industry, where competition is mainly based on price (Utterback and Abernathy, 1975). Pries and Janssen (1995) stated 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 (ETO) joinery-product suppliers in the Swedish construction industry (Forsman et al., 2011). Ozorhorn et al. (2011) stressed 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) asserted 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, 2004), Koskela and Vrijhoef (2000), Vrijhoef (1998, 2001, 2005), Vrijhoef and Koskela (2000), Ballard (1994, 2000, 2006), Ballard and Howell (1998), Howell and Ballard (1995) and Howell (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 (de Melo and Alves, 2010; Fontnini and Picchi, 2004; Polat and Ballard, 2003; Elfving et al., 2004). The mass-production origin of Lean seems to be a restraint for the adoption in this one-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) argued 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 is 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 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) showed 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 was to identify the main contributors to inefficiency and to define areas for innovation in improving this industry. Lean principles were 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 was 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 showed Swedish cases and thus represented 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”, “overproduction” of items not needed, “over-processing” with unneeded steps, and making “defective” products (Womack and Jones, 2003).

Liker (2004) presents 14 management principles used at Toyota that were 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 Hook 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) claimed that the evidence of waste in construction in terms of Ohno is overwhelming. Waste in those terms was 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; de 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 et al., 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 takt 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) was 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) stated 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. proposed 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). Zwikaël (2009) pointed 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 and Bröchner, 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; Forbes and Ahmed, 2011).

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 4-D 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, 1992). 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 USA 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.

Björnflot and Jongeling (2007) combined Line of Balance (LoB) with 4-D 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. 4-D CAD was used as a visualisation and analysis tool to evaluate and optimise the production plan and avoid clashes. Rwamamara et al. (2010) investigated 3-D and 4-D CAD visualisation techniques for planning construction from a health and safety aspect. 3-D and 4-D CAD not only makes a better planning tool compared with 2-D 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 3-D over 2-D was done by Santos and Ferreira (2008). Their studies provided 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. Generally, larger organisations have been better than smaller firms at making use of the results of process innovations. In manufacturing, the development and adoption of Lean principles has truly been an innovation that has also spread to other areas of society, health care and construction, for example, even if the extent is more limited in the construction industry. Still, study of the supplying of joinery products to the construction industry suggests that the adoption of Lean is limited, and the prerequisites for adoption of Lean 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 process studied in this work. Further, various kinds
of information-management tools and theories are seen as potential improvers for the situation in supplying joinery products to the construction industry.

Research methodology
The guiding purpose of this study was to gain detailed understanding of the practices and obstacles in supplying joinery products. With the focus on identification of main contributors to inefficiency and on the definition of areas for efficiency innovation, as well as on identifying occurrences of waste and their causes, questions of how and why emerged. These types of questions are closely connected to the hermeneutic data collection methods used. The emergence 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 stated objective. The qualitative method was chosen despite the fact that the mainstream researchers involved in this work have a positivistic ontology and find that the work is best described by measurements. The studies in this work were carried out as case studies with a qualitative approach; the purpose was to enhance knowledge of how the process works, what problems arise, and why the problems arise in the studied process and how the studied process tentatively could increase its process efficiency. According to Yin (2009), case studies are appropriate when the research problem requires understanding of complex phenomena that are not controllable by the researcher and when the research questions have a how and why nature; therefore, the case-study approach was chosen. 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 cases
The 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.

Plate 1 shows the products of the cases studied, which involve the supplying of joinery products to:

- an alteration project in an office building; and
- 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 were guiding:

- A description of the current process.
- Working conditions for the respondents.
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 respondents.

The interview respondents were practitioners in construction projects involving procurement of 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 were:

- the client procuring the construction project, the architects of the project;
- the site manager of the construction contractor;
- the construction engineer;
- the client-contracted construction coordinator;
- the construction contractor procurer of suppliers;
- the construction contractor surveyor;
- the construction contractor staff realising the environment adjacent to the joinery products;
- the sales manager of the joinery-products supplier sales organisation;
- the sales calculator of the joinery-products supplier sales organisation;
- the assembly procurer of the joinery-products supplier sales organisation;
- the production manager of the joinery-products supplier;
- the production pre-processing of the joinery-products supplier;

**Note:** From left: a reception and seating area, a shelf system, and a 12 floor massive wooden railing.
The manager of the contracted assembly contractor; and
- 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 were 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 1.

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

![Figure 1. Research design](image-url)
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 1). According to Merriam (1994), observing 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 about the process. The study was built on interviews, documentation, observations and six researchers’ views on the same study, this being a foundation for triangulation according to Yin (2009). 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 was 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 it can provide a reconstruction of development up to that point.

The analysis was focused on defining different types of waste surfacing in the studied cases as well as possible areas of innovation. The causes of these problems were 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 3-D measuring and modelling and principles of information management, are discussed.

**Sampling, validity, and reliability**

The sampling method was selective, supported by domain experts chosen for their specific knowledge. The unit of analysis was “process” from quote to assembly of supplied joinery products working inside the traditional construction process. The cases and the research method were chosen for their potential contribution to the overriding aim of this work. The study built on 65 interviews conducted throughout the value chain from sales to the assembled product.

Semi-structured interviews were used, conducted on site from 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 create the
significant contribution. The methodological approach was qualitative, with interviews, observations and documents as the data-collecting methods. To create reliability and validity in the work, triangulation was used in the use of data sources, the analytical model and in the fact that multiple researchers have looked at the same material and come to the same conclusions.

**Research findings**

The main aim of this paper was to identify the main contributors to inefficiency and to define areas for innovation. The findings section of the paper focused on presenting the nature of the process of supplying joinery products to the construction industry as found in the studied cases.

The process of supplying joinery products to construction is shown in Figure 2. This value stream represents the process used by the organisation in the studied cases. The study is delineated to cover the process from quote to assembly on the construction site.

**Quote to order**

The sales process targets the traditional construction industry. Generally, construction contractors send out quotation requests to possible suppliers in two cases:

1. when the construction contractor is 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; and
2. when the construction contractor has 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 processed by the sales company, which estimates cost and market value in making the quote. The products are often prescribed by an architect, who expresses the client's needs into governing documents and drawings. In making the quote, this information is used by the sales department to understand the request and to estimate the price. Depending on the level of complexity of the product in the quotation request and on the level of predetermined quotation systems between the sales company and the specific production company, quotes are sometimes made without direct contact with the production pre-processing, which is the instance that defines the information into a product. When the sales department receives the order, accumulated information from sales is transferred to the production pre-processing section. In the studied cases, the procurement was done on a project level. In the first case, the procurement took 15 weeks, out of which the supplier processed the quotes for three weeks. After the order was received, ten weeks were used for engineering, producing and assembling.
assembling the products on site. In the second case, 96 weeks were spent on procurement, and out of these, the supplier processed the quotes for six weeks. Then 21 weeks were spent on the steps from ordering to completion of the assembly.

**Surveying**

When the order is received, the joinery-product supplier needs to survey the built environment before manufacturing is started. Precise control of the geometrical information is needed in order to complete the production pre-processing, and due to uncertainties in the current methods, it is not unusual to some extent to need to carry out the surveying more than once. The reason for the surveying is that joinery production requires tighter tolerances than in construction in general. The precision of the geometrical information in provided drawings, in comparison to the as-built reality, have proven to be insufficient 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.

This surveying, currently, involves manual measuring performed on site, generally by the supplier. The experiences of the respondents show that a majority of the construction projects work with 2-D drawings as the main information carrier. In these cases, the results of the manual measuring were noted on 2-D 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 time required to perform the measurements varies from a few hours to hundreds of hours, depending on project conditions, and needs to be estimated from the prescribing documents when making the quote. The studied cases have shown that 3-D anomalies (e.g. floor-wall angles other than 90° and surface unevenness) were not revealed by the manual (2-D) measurements, and it was seen that this limited the degree of prefabrication of the joinery products, leaving more work to be performed when assembling the joinery products on site. The making of the measurements on site required coordination with the construction project, and it is not unusual to need 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 Plate 2, where sheet-metal sleepers on the floor show where a future wall would be built.

**Plate 2.**

**Note:** 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.
Production pre-processing

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 begins. This work is done in production pre-processing at the production company. 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 sub-contractor and results from the on-site surveying. This information is processed into work orders for the production machines and personnel as well as ideas for assembly methods. The main information carriers are 2-D drawings, manufacturing bills and a production plan.

In the cases studied, there was not any direct communication between the joinery-products supplier and the prescribing architects, despite the fact that the architects have expressed a wish to communicate with the joinery-products suppliers. To establish such contact, the construction contractors need to give approval for the joinery-product supplier to communicate with the architect.

Much of the defining work was performed by a single person in production pre-processing in the studied production companies, a role with periods of high workload. The main support for this work was CAD software and the companies’ own routines developed for creating manufacturing bills and production plans for the production staff. It was noticed that the quality control of this function was limited, 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 Plate 4.

Manufacturing

In the cases studied, the manufacturing took place at production units run as own companies with less than 20 employees. The manufacturing of the products was performed using information from pre-processing. This information was communicated mainly by 2-D drawings and a manufacturing bill, and a production plan was used to show the manufacturing time requirements.

Both numerically-controlled and manually-controlled machines were used in a fixed floor layout. To be able to produce different types of products, multipurpose machines were used together with flexible material routes. When the joinery-product components have been assembled at the planned level of prefabrication, groups of product components are put together in parcels. In the making of parcels, focus was mainly on establishing sturdy parcels, and the components within the parcels where claimed to be labelled.

Each of the production units runs its own process and technology development. Together with the sales company, each production unit develops its system for price estimation that normally is performed by the sales company.

Logistics. Transport to the construction site was performed by a forwarding agent, which is the normal routine for the studied suppliers. Once the parcels left the production unit, the supplier had limited control over the time of arrival at the construction site. The arrival of the goods shown in Plate 3 was one day later than scheduled, and allocation of external contractors was done without being able to make use of them. Observations showed that the level and existence of labelling on components in the delivered parcels varied which complicated the understanding
of the delivered components for the assembly contractor and slowed down the pace of assembly. It was seen that the arrivals of deliveries were not coordinated with the assembly needs, but rather with the time of manufacturing, and therefore components had to be stored on site while waiting to be assembled.

Plate 3 shows the activities that were involved in receiving parcels on site. The first consideration for the assembly staff was to determine how to transport incoming parcels into the building. Second, the contractor for receiving the goods had to wait for the tractor needed to unload the parcels from the truck. Third and fourth, 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. This procedure also exposed the joinery components to increased risk of damage.

Assembly
In the end of the supply value stream, the joinery-product components are assembled and installed at the construction site by an assembly contractor. Here, the final value adding to the joinery products takes place. The assembly of the joinery products normally takes place in the final stages of the construction project and often consumes up to half of the supply budget. This work is usually done under the pressure of time due to limitations in when the work can start, and a delayed assembly can affect the constructor contractor’s ability to meet time requirements.

When the product order is received, the assembly planning is performed concurrently with the manufacturing value stream by resources at the sales company. The main tasks of the assembly planning are to contract assembly and to coordinate assembly with the manufacturing of the production company. Since projects are geographically spread out, the strategy applied is to contract assembly contractors close to the construction site. 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, but normally the assembly contractor needs a large proportion of ad hoc problem solving and on-site coordination with other contractors to perform its work.
When performing assembly on site, the assembly contractor needs information to understand how to accomplish the assembly of the ETO products. The main information carriers to support this understanding are 2-D drawings from the architect, and occasionally some sketches or drawings from production pre-processing. Due to differences between architectural drawings and as-built reality, the information in the architectural drawings can differ from those provided by production pre-processing that is based on data from surveying. Such differences in the assembly information have occurred in the studied cases, and observations showed that differences between architectural drawings and sketches from pre-processing were not easily detected. Assembly instructions or exploded views are usually not supplied to the assembly contractor. This level of information exchange generated a need to establish direct communication with production pre-processing in order to develop an understanding of how to assemble the product. Observations showed on several occasions that when the assembly contractor needed to communicate directly with production pre-processing, that person were not available. This was seen to interrupt the flow of assembly as well as the workflow for the production pre-processing. The assembly contractor highlighted the need for information that would be easier to interpret, such as 3-D views.

When the assembly started, the date when the work was supposed to be complete was known, but detailed takt planning for the assembly was lacking. The detailed production design of the assembly work was performed by the assembly staff in cooperation with production pre-processing and started when the components of the joinery products arrived at the construction site.

Carrying out the assembly on site involved coordination with other contractors on site, and much of this coordination was left to the assembly staff. This was a significant part of the time used in the assembly work studied. Lack of coordination often generated changes in which work should be in hand.

Many of the small problems faced in the assembly work were solved ad hoc and 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, and similar problems were seen to reoccur.

When supplying an ETO joinery product, the design of the product, the production and the assembly needs to be done in every specific project. Under the pressure of providing short lead-time, limited focus is put on the design part of the process, and observations reveal that under-processing in design caused efficiency losses in the assembly. Plate 4 shows some aspects of this. First, the chosen production method for the shelving base that should be managed by the assembly took a considerable amount of time. The next two parts of Plate 4 show a logical error in the production pre-processing that passed through design and manufacturing and added rectifying work for the assembly contractor. The final picture in Plate 4 shows how an adjacent process positioned cast-in anchor points in a concrete stair that did not fit the design of the prescribing documents. The consequence was a significant increase in assembly time of the joinery products.

Analysis
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 analyse the process as described above and the
problems observed that are seen to affect the efficiency of the joinery-products value stream when studied against the above-mentioned theories.

The Lean methodology is used to define wastes occurring and to find their root causes. It is evident from the case studies that waste is present in the process of supplying joinery products to construction. By using a Lean perspective, the ability to see problems emerged, and asking why is used to find their causes. Therefore, problems encountered late in the supplier process, for example in assembly, are seen as symptoms whose root causes are likely to be traceable upstream.

Waste occurring
From the findings, various problems in the process have been presented. The following model presents wastes found in the described process seen from a Lean perspective using the seven wastes of Taiichi Ohno. In the analysis, we find that overproduction does not apply well to the ETO production studied. The findings related more to under-processing, which we define as: deficiencies in information and materials forwarded through the value stream causing inefficiency in downstream processes. In the model used here, overproduction is therefore replaced with under-processing, and thus the acronym TIMWOUD is used in the presentation of wastes in Table I.

Quote to order analysis
In Lean, continuous flow is advocated. In the studied cases, procurement took more calendar time than the time that was used for realising the product. For a large extent of the project time, the information on the architectural product specification was idle before the joinery-products supplier added value to the given information when doing the product definition after the order was received. The model of procurement of the suppliers hampers the establishment of communication between those adding value to the product and thus violates the principle of continuous flow of information and obstructs a concurrent engineering approach, which is known to shorten lead-times and increase quality and information exchange (Sohlenius, 1992; Karlsson et al., 2008).

Surveying analysis
Lack of reliability in supplied geometrical information creates the need to perform surveying on the construction site during the production pre-processing of the
| 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  
| | Lifting 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 unpacking motions (Plate 3)  
| | 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 that do not arrive  
| | Assembly work being put on hold due to absence of information  
| “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 (Plate 4)  
| | 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  
| | Insufficient communication of 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 takt time  
| | 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 (Plate 4)  
| | 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  

Table I. Identified TIMWOU (Waste) Need for Innovation in ETO
joinery products. Here, the needed quality in the geometrical information is not available and needs to be created. The responsibility to create the needed spatial information is generally left to the supplier, and there is no incentive in the supply chain management to develop the efficiency and quality of the surveying. This lack of mutual incentive for process development is a known phenomenon in the construction industry (Vrijhoef, 1998; Aouad et al., 2010). With the methods currently used by the joinery-products supplier in surveying, there are still spatial uncertainties that have not been eliminated. The current methods used work on a 2-D level and with few measurement positions and cannot, therefore, detect the all 3-D anomalies in the as-built environment that need to be considered in the alignment of the joinery products to the as-built environment. Further, the manual measurements represent a risk if they prove to be insufficient, inaccurate or more time-consuming than planned for in the quote. The surveying itself causes expenses for transport, motion, etc. but the more major impact on the cost of the supply process comes from the uncertainties of spatial information that seem to be substantial, since these cause waste at several levels of the process.

Production pre-processing analysis
Production pre-processing is a key function in the value stream of supplying joinery products. Here, all requirement information and business information is used to define the product, its production and assembly methods, the production planning, etc. Much information is needed, and the outcome is also information. The quality of this work highly affects the rest of the process. Still, the quality of the incoming information remains uncertain, and the possibilities for modelling different scenarios are limited due to limitations in tools for this and to the need for information about adjacent processes in order to enhance coordination and collaborative efforts, which Anumba et al. (2008) point out requires effective communication of project information between project participants.

The model of procurement of the joinery-product supplier also affects the possibilities for production pre-processing to communicate with the prescribing architects in order to enhance the quality of understanding of the prescribing information.

Further, the often short-term planning puts high pressure on this function that is often managed by a single person in these small production companies. For these reasons together, the outcome of production pre-processing is also likely to have limitations in the level of information processing and quality, and this affects the efficiency of the downstream processes.

Manufacturing analysis
Increased level of prefabrication would be desirable from the standpoint of manufacturing. Limitations to success in this endeavour are due to limitations in the available information. With numerically-controlled machines, precise alignment of the joinery products to the surrounding environment would be possible if spatial information as well as other construction processes where available in digital format that could be modelled to determine the “optimum” solution. To achieve this, the use of theoretical knowledge and technology needs to be implemented in developing the processes, and this is a difficulty in the studied production companies that have limited resources for such work.
Logistics analysis
The study shows that considerable amounts of waste, supply chain disintegration and lack of coordination are present in the logistics that affects suppliers' performance. Similar to the way Xue et al. (2005, 2007) describe inter-organisational problems, there are several operational processes here that need to be synchronised, and that information needs to be exchanged.

Lack of synchronisation precision caused unnecessary resource allocation, and limitations in look-ahead planning caused uncertainty about the transport routes at the construction site. The cause of this was that in the parcel design, the spatial limitations of the transport routes were not considered. Drawings with this information were not available to the supplier, and neither was any digitised information that could be used to model transport routes for the parcels with the joinery-product components.

This unawareness of the on-site transport routes considerably increased the time for the receipt of the deliveries and also severely increased the risk for damage to the manufactured components. The lead-time to produce new components for such ETO products can delay the project, which in turn can jeopardise the supplier’s profitability for the project if the construction contractor should raise penalty claims.

The integration of the transport service provider and the supplier process would be a desirable innovation in which the service provider expands its responsibility to involvement with the transport of the components from manufacturing site to assembly location on a just-in-time basis.

Assembly analysis
In the assembly phase, considerable waste manifests whose causes can be found upstream in the supplier value stream. With a reduction of waste in assembly using Lean principles and with focus on improving efficiency, a reduction of the time needed for assembly at the construction site would be possible, and this would strengthen the competitive advantage for the supplier. An increase in the level of forward planning would be beneficial for the predictability of work releases that Howell (1999) shows is essential in establishing a Lean process.

Efficient information transfer through the value stream is needed, and modelling this information to make it easier to take in and understand is a key issue. Currently, the level of information exchange is insufficient and has to pass various organisational borders that are known to restrict information exchange. The limitations in the available information cause uncertainties that slow down the pace of assembly. Here, the use of accurate 3-D models with the as-built information would be useful in increasing the speed of understanding and decreasing logical error in component design and manufacturing. Visualising the information needed for assembly planning using line-of-balance and 4-D CAD would be beneficial for the coordination of collaborative resources.

In the assembly, ad hoc problem solving is normal, and this culture limits the detection of problems. Similar problems reoccur repeatedly without any investigation as to why they occur. This limits organisational learning. Increased education in Lean principles throughout this supply chain in order to increase awareness of this phenomenon and to create a platform for continuous improvements would constitute a useful innovation.
Discussion
As the main aim of the paper was to define the main contributors to inefficiency and to define areas for innovation, considering this increased knowledge about waste occurring in this area of the construction industry was essential to improve the performance of the supply process. The causes of detected waste are examined according to the principles of Lean and information management.

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 in the supplier procurement. 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:

1. Inadequate planning and coordination.
2. Absence or inadequacy of assembly information.
3. Spatial uncertainties.

All three relate to sharing, exchange, and modelling of information. From a Lean perspective, process flow is central. Takt and just-in-time 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
Areas for innovation

In Figure 3 a generalisation of the observed problems of the seven wastes of Lean is developed, illustrating the efficiency potential of eliminating waste.

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.

**Figure 3.** Waste elimination as a means of improving process efficiency

*Source: After Koskela (1992)*
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 questioned 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 20 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 4 shows 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.

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 3-D CAD models would be

Figure 4. Potential of concurrent engineering approach
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 overproduction in production and assembly. Different 3-D 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.

Conclusion
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.

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:

(1) Inadequate planning and coordination.
(2) Absence or inadequacy of assembly information.
(3) 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.

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:

(1) Long-term philosophy.
(2) Standardisations in process and communication.
(3) Development of individuals and partners.
(4) 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 3-D 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.

References


**Further reading**


**Corresponding author**

Samuel Forsman can be contacted at: samuel.forsman@ltu.se

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Model-based production for engineered-to-order joinery products

Authors:
Niclas Björngrim, Lars Laitila, Samuel Forsman, Peter Bomark

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MODEL-BASED PRODUCTION FOR ENGINEERED-TO-ORDER JOINERY PRODUCTS

Niclas Björngrim¹, Lars Laitila², Samuel Forsman³, Peter Bomark⁴

ABSTRACT: When supplying Engineered-To-Order (ETO) joinery products to the construction industry, the manufacturer often takes responsibility for the whole value stream, from request for quotation to final assembly on the construction site. There are, however, gaps in the information flow between each actor in the internal supply chain, leading to quality concerns. One of the issues comes from the lack of routines concerning documentation of both changes and additions to the original plan. To make up for the lack of documentation, the craftsmen rely on their skills and experience, often leading to unnecessary and time-consuming ad hoc solutions. Each actor in the chain spends time rediscovering previously known information instead of referring to the documentation. In this paper we suggest a model-based approach, utilizing information and communication technologies (ICT) that enables improved dissemination of relevant information to the involved actors.

KEYWORDS: ETO joinery production, Model-based production, information and communication technologies (ICT)

1 INTRODUCTION ¹

When supplying ETO joinery products for the construction industry, the ETO joinery-products supplier often has responsibility for the whole value stream from quote/order through surveying, production preprocessing, manufacturing, logistics and final assembly on the construction site [1, 2]. Important information in the supply chain is lost and does not reach all the actors involved in the internal supply chain. Forsman et al. [2] found that there is a large amount of waste present when supplying joinery products for construction and suggests that information and standardization in communication are main areas for improvement. The joinery-products suppliers’ process could be enhanced by utilizing 3-D measurement techniques and information and communication technologies (ICT) tools such as Building Information Model (BIM) [3], Last planner [4], Line of Balance (LoB) together with 4-D CAD [5], etc. These tools could help increase dissemination of information in the joinery-products suppliers’ internal value stream. BIM is interesting for the information sharing. However, the information in 3-D BIMs does not generally contain details of a facility and therefore does not reflect how the building actually was built [6]. Joinery-products suppliers need as-built information rather than planned spatial spatial information as a basis for production. The objectives of this paper are to introduce a more efficient information carrier than 2-D drawings. A 3-D model based approach is proposed.

2 METHOD

The focus in this study has been on gaining detailed understanding of the information flow in the value stream for ETO joinery-product supplier supplying to construction. A Swedish ETO joinery-products supplier has been observed through one of its projects. The studied joinery-product supplier is a Swedish association consisting of ten production companies and a co-owned
sales company. Attention has been paid to the information flow from quote/order, surveying, production preprocessing, manufacturing and logistics to final product assembly on the construction site. During surveying, the information needed for defining the products is acquired, and this information is assumed to be of major importance. The lack of information through the internal value stream is assumed to materialise during the assembly, hence the special attention on surveying and assembly. The case study also consists of semistructured interviews with key personnel from the departments responsible for sales, production preprocessing, manufacturing, logistics and assembly. The interviews focused on how the organization relates to the surrounding actors. On-site observations were performed during surveying, during manufacturing in the production facilities and extensively during assembly and have been documented through notes, photographs and audio recordings. To improve the productivity for joinery-products companies, ways to improve the internal process through modelling of information and coordination have been explored. Potential improvements in efficiency resulting from the application of new technology such as 3-D measuring and modelling and principles of information management are discussed.

3 RESULTS AND DISCUSSION
Here the current process for the joinery-products supplier is described and ways to improve the process are discussed. Figure 1 shows the value stream of the current process.

Figure 1: The value stream from quote to assembly.

3.1 QUOTE/ORDER
Generally, sales process quotes are made in two steps, a preliminary quote for construction contractors making a quote to a client and a final quote to the construction contractor who received the client order. This procurement process normally involves supplier competition. Sales base their quote on the architectural drawings. By using a BIM, the joinery-products supplier could have a better basis for pricing their product.

3.2 SURVEYING
The production preprocessor determined important dimensions from the architectural drawing. Those dimensions where later measured at the construction site by a surveyor. The current process relies on manual measurement techniques done with folding rulers and tape measures, with 2-D information written directly on a printout of the architectural drawing (Figure 2). The printed drawing acts as the main carrier of information. Faults in drawings can be difficult to detect until on-site assembly has begun. The geometrical information is needed to complete the production preprocessing, and complementary measurements were needed to get all important dimensions. By using 3-D digitizing equipment, the surveying would provide the production preprocessor a complete and accurate depiction of the site. The 3-D data depict the whole on-site environment and negate the need for eventual secondary on-site measurements. For capturing the correct construction site data, coordination between surveyor and construction contractor is necessary.

3.3 PRODUCTION PREPROCESSING
The surveyors’ geometrical verification in 2-D is the basis for defining the joinery products’ dimensions. The production preprocessor defines a product from the given dimensional information, develops production methods and schedules the production start. Since joinery production requires tighter tolerances than construction in general, there is a need to verify the geometrical shape of the environment and compare it to the construction drawings. The geometrical verification leads to dimensional uncertainties. The dimensional uncertainties make it necessary to produce products to be adjusted to fit during the on-site assembly. With an accurate 3-D depiction of the adjacent environment, joinery products could be produced to fit without adjustments.

3.4 MANUFACTURING
Manufacturing of the products is performed on the basis of information from preprocessing. This information is mediated mainly on 2-D CAD drawings and a manufac-
turing bill. A production plan is used to show the time demand for the manufacturing. Errors in the joinery product are hard to discover from the 2-D model. A 3-D CAD model gives the opportunity to inspect the joinery product before manufacturing and can minimize time-consuming design errors (Figure 3). 3-D CAD also gives the opportunity to automatically generate tool paths in CAM software.

![Figure 3](image3.png) Design error, the laminate is missed on the top of the lower shelf.

3.5 LOGISTICS

After manufacturing, the products are packed to fit on the pallet, rather than grouped to facilitate assembly. A product declaration of content is supplied with the parcel; however, observations show that this is an area of frequent failure. Lack of complete information caused delays in assembly when the personnel had to open several parcels to find the related components. There was no concern of the internal logistics on the construction site when the parcels were put together. The parcels did not fit the in-transport routes of the site, forcing the assembly personnel to open the parcels and carry the components to the right floor (Figure 4). This is not only time consuming, but also involves the risk of damaging the joinery products and causing injuries to personnel due to bad lifting positions. The shipping of parcels should be coordinated with the needs of assembly, rather than the time of manufacturing. Visualization of in-transport routes and the final product could eliminate these problems.

![Figure 4](image4.png) Parcel opened and carried into elevator due to parcel design not fitting in-transport route.

3.6 ASSEMBLY

The planning of the assembly is performed concurrently with production. Since projects are geographically spread, the strategy applied is to contract assembly contractors close to the construction site. The main tasks of the assembly planning are to contract assembly and coordinate with production. The product assembly is performed on site and requires time to develop understanding of the product to be assembled. During assembly, there are no instructions provided, and the information from the 2-D drawings is used as support, sometimes with additional sketches from the preprocessor. Having a 3-D model of the site would be of help for the construction personnel to visualize the joinery product and the environment where it will be assembled. Assembly instructions or exploded views were not supplied to the assembly contractor. The planning of the assembly has a start date and a stop date, but there is no daily or weekly planning. Coordination between the manufacturer and assembly personnel is needed as well as with other actors performing work on the construction site. The assembly contractor needs to communicate with the production preprocessor in order to develop an understanding of how to assemble the product. Communication was done by phone, but could have been avoided if good assembly instructions had been
provided. Because of the lack of spatial information about the construction site, products are manufactured to be adjusted to fit. This process requires lot of craftsmanship instead of assembly work. Assembly problems are solved ad hoc and the root of the problems is not investigated. Having complete spatial dimensions of the site would increase the level of prefabrication of the joinery products, thus making assembly rely less on craftsmanship and more on installation work.

3.7 MODEL BASED PRODUCTION

To enhance the process and keep the information updated and accessible for the suppliers in the whole value stream, we propose a 3-D model-based process as seen in Figure 5. Information is created through the whole value stream and information dissemination between the actors is improved. In order to improve the quality of joinery products for construction, more of the as-built spatial information needs to be known and to be more accurate than in the current process. The 3-D information must be based on as-built dimensions rather than as-planned spatial dimensions of BIMs [6]. To facilitate dissemination of project information to the different actors in the internal value stream, it is suggested that all information be retained in digital format. When sales receive the order, a visualization of the site provides a better basis for estimating the quote. Surveying with a 3-D digitizer enables acquisition of the spatial information needed for creating products with good fit and provides a tool for visualizing and planning of assembly. By using 3-D CAD, the fit of the model can be assured virtually in the 3-D scan or in a surface/solid model created from the scan data (Figure 6).

The model consists of a wide range of information such as dimensions, surface finish, tolerances and URLs. In this stage, the model can also be prepared for machining (CAM). If the manufacturer has a better understanding of the final product, it is easier to send parcels with the right components at the right time. The manufactured parts can be sent correctly packed, in parcels that fit in transport routes at the construction site. The visualization of the site is used to make sure that parcels will fit in transport routes, eliminating the need for repacking of the parcels. During the assembly, the 3-D scan together with the CAD models can be used with various planning tools [3, 4] to make assembly more efficient by visualizing where a product should be placed and when.

4 CONCLUSIONS

In the current process, the main information carrier is printouts of architectural drawings with added information. This information can be difficult to interpret and needs to be further processed in order to create CAD models for production. The information in the drawings offers little support for the assembly. A higher degree of utilization of ICT and planning tools is suggested in order to create accurate and accessible information for all actors in the internal value stream. When information is available to all involved actors early in the process, a more concurrent approach is possible, which means that several tasks can be done in parallel. Providing better spatial measures results in joinery products with higher quality and better fit, which will make assembly less time consuming. The knowledge gained from different projects could be accumulated and used to facilitate future projects.

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REFERENCES


Real-World Three-Dimensional Measuring of Built Environment with a Portable Wire-Based Coordinate Measuring Machine

Authors:
Samuel Forsman

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Real-World Three-Dimensional Measuring of Built Environment with a Portable Wire-Based Coordinate-Measuring Machine

Samuel Forsman

Abstract

A long-term strategy within the forest products industries is to increase the products’ refinement and thus their value. This strategy applies to both primary and secondary processed wood products. Further down the value stream, different kinds of knowledge are needed in order to add value and efficiency in the supplier process. In this study, the focus was on as-built three-dimensional (3-D) sensing as a means to increase the level of product prefabrication when supplying engineer-to-order joinery products to the construction industry. A 7-m ranging three-axis portable wire-based coordinate-measuring machine (PWCMM) was evaluated in terms of performing as-built site-dimensional verification in 3-D. This is a needed means for moving the fitting of joinery products into the digital domain at the design stage, thus increasing the level of prefabrication and automation possible when supplying engineer-to-order joinery products. The PWCMM has been used to replicate different construction sites to gain as-built spatial information as input into the suppliers’ design, manufacturing, and on-site assembly processes. The evaluation shows that the accuracy in each coordinate position can be within a millimeter range. However, questions still remain about the capability to meet the demands on accuracy and usability for on-site dimensional verification when supplying joinery products. Issues with error leverage and low measurement resolution limit the practical possibilities in terms of level of accuracy and detail of the reproduction of the as-built environment.

The sawmill industry has a tradition of supplying vast volumes of primary-process wood products with limited refinement value to vast geographical areas. This generates significant export incomes for world-export-leading countries like Canada, the United States, Sweden, and Germany (Swedish Forest Industries 2013). However, these products face challenges with demand, and an expressed strategy within this industry is to increase the products’ value refinement. The secondary wood processing industry also struggles with this strategy. This study focused on supplying engineer-to-order joinery products, henceforth referred to as “joinery products.” This is a secondary wood-processing industry, with the construction industry as the major customer. Worldwide, the construction industry is one of the most important elements of every economy and the major customer for most wood products. Therefore, increased interaction with this industry has the potential to reveal value-adding opportunities for wood products.

Joinery products are highly refined one-of-a-kind wood products such as entrances, glass partitions, doors, windows, interiors, cabinet fittings, special fittings, stairs, etc., designed to fit specific customer needs. These components are engineered and manufactured in factories off site, where they are packaged and transported to the construction site where they are assembled. This is a process with two main parts: (1) factory production, which is more efficient, and (2) work at the construction site, which is less efficient and/or labor intensive. The amount of labor-intensive work at the construction site is dependent on the level of product prefabrication and on how well the finished joinery products fit the intended location. Reliable as-built spatial data from the construction site are crucial to the manufacture of joinery products that can be assembled efficiently. Currently the assembly work often consumes half of the joinery-product supply budget, and manual fitting of components is a major contributor to the time consumption of the assembly work. Therefore much value refinement can be achieved through improved interaction with the customer and improved on-site assembly efficiency through decreasing...
spatial uncertainties regarding the environment ambient to the joinery products.

The use of building information models (BIM) is increasingly implemented in the architecture, engineering, and construction (AEC) domain. These semantically rich three-dimensional (3-D) models that store information in a single integrated source were originally developed to enhance planning, visualization, and communication during design, and to aid in the detection of mistakes during construction, process simulation, and space planning during management (Sacks et al. 2004, Akinci et al. 2006, Eastman 2008, Xiong et al. 2013). With a history of being created during design, the as-designed or as-planned BIMs are the predominant BIMs in the AEC domain. These BIMs may vary significantly from the actual current condition, the as-built or as-is conditions of the facility. These differences arise from a variety of sources, such as undocumented design changes, inadvertent errors in the construction, and renovations during the ensuing period (Xiong et al. 2013).

There is, therefore, a need for BIMs based on as-built or as-is conditions. Hereafter as-built is used to refer to both terms. Further, as-planned is used to include to both as-planned and as-designed terms.

The generation and use of as-built geometrical conditions in construction has gained momentum in the research literature, covering such areas as quality-assessment, progress and productivity monitoring, materials tracking, and automated routing for construction vehicles. (Tang et al. 2009, Huber et al. 2011, Turkar et al. 2012, Anil et al. 2013, Argiellès-Fraga et al. 2013, Kim et al. 2013, Xiong et al. 2013, Bosché and Guenet 2014, Bosché et al. 2014). Much focus is on automation of the process of acquiring the as-built geometries from different 3-D sensing technologies (Anil et al. 2013, Kim et al. 2013, Xiong et al. 2013). In the following, I focus on achieving as-built geometries from construction sites that can be used as a means for increasing automation within the process of supplying joinery products.

Uncertainties of as-built geometrical conditions with currently used methods for as-built verification have been shown to cause a number of types of waste in the supplying of joinery products: unnecessary transports, motions, waiting, overprocessing, overproduction, and defects (Forsman et al. 2012). Potentially, much of this waste can be eliminated through different automation actions based on BIMs with accurate as-built geometries and with semantics of the construction process. Here are three examples of automation actions that would eliminate waste: (1) move manual fitting from the end of the supply process to the digital environment early in the supply process in order to allow automatically performed product-to-room fitting and to allow use of numerically controlled machinery to perform the physical fitting on the product components; (2) because of size limitations of in-transport routes on site, design the size of the parcels in the digital domain to optimize on-site delivery; (3) synchronize the supply process to the construction process by ensuring that the environments adjacent to the joinery products have been prepared for the assembly of the joinery products. These examples show that increased certainty of as-built geometrical conditions has the potential to vastly improve the efficiency of supplying joinery products to the construction industry.

The purpose of the study was to evaluate whether a portable wire-based coordinate-measuring machine (PWCMM) is sufficiently accurate and usable to perform practical as-built site verification in 3-D to a level where fitting of joinery products can be performed in the digital domain during design.

The hypothesis is that the PWCMM can eliminate dimensional uncertainties of as-built construction sites to a level on par with joinery-product tolerances and meet practical usability demands. Investigations on sensor accuracy and effects on measurement uncertainty when using the PWCMM functionalities are presented together with accuracy and usability experiences from four cases. The original contribution of this article is on 3-D sensing of construction environments with a PWCMM and generating digital models of the real world that can be used for fitting of joinery products in the digital domain during design.

Theoretical Overview of As-Built 3-D Measuring

Measuring geometries in 3-D is a widely used technology in many different industrial applications. The general purpose is to achieve as-is geometrical information of the measured object (Pereira and Hocken 2007, Cuypers et al. 2009, Barini et al. 2010). The culture of ensuring the correct geometrical shape of components has been the foundation for industrialized processes. This is exemplified by Henry Ford and the use of interchangeable components. Currently three major technology categories can be identified: (1) coordinate-measuring machines; (2) laser scanners; (3) optical measuring techniques. These three methodologies are used in different industrial contexts and with a different resolution and scale depending on application. In the following, focus is on coordinate-measuring machines (CMMs). CMMs translate the positions of the measurement probe to a 3-D coordinate system (Schwenke et al. 2008). Two types of CMMs can be identified: conventional CMMs and portable CMMs. Conventional CMMs are stationary and are widely used in control stations in the manufacturing industry. These are highly accurate (0.3 to 2.0 μm), but they normally control positions on an object with a known 3-D model rather than depicting an object and generating a 3-D model from the coordinate observations (Barini et al. 2010, Leitz Metrology 2014, Nikon Metrology 2014). Two types of portable CMMs are most common, articulated arm coordinate-measurement machines (AACMMs) and optical portable CMMs. The AACMMs are measurement arms and have five to seven rotary joints or axes and measure with ASME B89.4.22 single-point accuracy of 20 to 140 μm within a working range of a 1.5- to 4.5-m radius (American Society of Mechanical Engineers [ASME] 2004, Sladek et al. 2013, Hexagon Metrology 2014). Optical portable CMMs are optical camera-based triangulation systems with a handheld probe. The probe positions are sensed through markers on the probe, whose position is compared with a set of reference markers. The ASME B89.4.22 single-point repeatability is 37 to 95 μm, and the working range is a coordinate system up to 17 m³ (Cuypers et al. 2009, Creaform Measurement Solutions 2014, Nikon Metrology 2014).

The majority of research about CMMs concerns conventional CMMs, and Cauchick-Miguel et al. (1996) claimed that their measurements could be influenced by a wide range of errors. This is reflected in much of the subsequent research, for example, uncertainty in coordinate measure-
In these cases, the PWCMM was used for 3-D sensing of
as-built construction-site dimensions. The machine capabili-
ties and case experiences of the PWCMM measuring have
been evaluated against the potential of eliminating spatial
uncertainties through the following criteria:
1. Accuracy, i.e., opportunities to eliminate spatial uncer-
tainties of the construction site to a level on par with
claimed tolerance requirements on joinery products (≤1
mm) and preferably meeting the “golden rule of
metrology,” wherein measurement uncertainty should
not exceed a tenth, or at most a fifth, of the toler-
ance requirements, thus ≤0.1 to 0.2 mm (Beckert et al.
2010).
2. Usability, i.e., opportunities for adapting the technol-
ogy to the joinery-product supplier’s process. This concerns
issues such as measurement range, portability, informa-
tion quality, efficiency in performing measurements and
the necessary data processing, level of expertise needed
to operate and to reconstruct 3-D geometries for
measurement purposes, quality improvements in project
information communication, and ways information
quality might enhance the manufacturing and on-site
assembly processes.

Accuracy testing of PWCMM sensors

The Proliner 8 PWCMM registers the position of a stylus
probe as coordinates in a Cartesian coordinate system. The
stylus probe is connected to the machine with a wire
extracted from a measurement arm that can rotate in both
horizontal and vertical directions (Janssen 2004, Prodim
2014). The machine has three sensors, one for the wire
extraction, a second for the measurement arm’s horizontal
position, and a third for the arm’s vertical position. The
range of the wire is up to 7 m, and the measurement arm
can be rotated 40° horizontally and 104° vertically. Coordinate
registrations are performed with a stylus probe positioned on
an object, and the user operates a remote control to order the
machine to register that position (Fig. 1). The measurements
are presented to the user on the screen of the PWCMM. The
output data from the PWCMM measurements are stored as
DXF files that can be transferred to most computer-aided
design (CAD) software.

To test the accuracy of the PWCMM, the random error of
measurement registrations when using the PWCMM was
measured. This gives a PWCMM user an understanding of
the possible accuracy that could be expected from the
measurements without the need for special equipment. By
using only supplied components, this test can be performed
by any user of the PWCMM.

The experimental setup uses the PWCMM and four
mobile reference targets. With these reference targets glued
to the ground, fixed measurement registrations can be made
owing to the support they provide to the stylus probe of the
PWCMM. Each measurement position in the tests uses these
to fix the measurement probe when recording the observa-
tions. The performed sensor tests use a fully randomized
design with 30 replicates.

Wire-extraction sensor test setup.—The setup for testing
the accuracy of the PWCMM wire-extraction sensor used
four reference targets fixed on the floor along the 7-m range
of the wire extraction (Fig. 2). The wire-extraction positions
recorded were 100, 280, 470, and 650 cm from the machine
origin. The horizontal sensor position was fixed, and the
vertical sensor positions were 1°, 5°, 3°, and 2°. In the

Methods

3-D sensing of as-built construction site geometries with a
portable wire-based coordinate-measuring machine, the
Proliner 8 (Prodim 2014), was studied in the context of
supplying joinery products. Machine accuracy and usability
were analyzed from the perspective of increasing automa-
tion within the supply process by moving the product-to-
room fitting to the digital environment. Machine capabilities
were examined, and data from four cases were captured
through interviews, direct observations, participation, and
control of documentation. Documentation from notes,
photographs, and documents was the basis for analysis.

In construction-related research of as-built measuring,
other 3-D sensing technologies are used, most commonly
laser scanning. The focus on measurement accuracy in this
research is limited, but some research that quantitatively
instruments (Wilhelm et al. 2001), sources of geometry errors
(Schwenke et al. 2005, 2008), dynamic errors of CMM
(Jinwen and Yanling 2011), and separation of machine and
probe errors (Naï et al. 2011). Much of this research is
about understanding measurement uncertainty and suggests
that the levels of uncertainty of the conventional CMMs are
small in relation to geometric accuracy in the construction
industry. However, conventional CMMs are stationary and
therefore not feasible for measuring as-built geometries at
construction sites.

The research on portable CMMs is more limited, but still,
considerable effort has been devoted to understanding the
uncertainty of the measurements and calibration and error
correction. Shimomina et al. (2002) suggests a calibration
method with better performance than the accuracy specified
by the manufacturer. This is needed because of difficulties
with traceability of the measuring machine, since calibration
is done by the manufacturer and by an unpublished method,
a situation similar to the studied PWCMM. Other research
deals with identification and modeling of the AACMM
errors and proposes correction handling for improving
performance (Santolaria et al. 2008, Sladek et al. 2013) or
finding the optimal measurement area (Zheng et al. 2012) or
suggests correction models for thermal errors that do not
affect the calibration conditions (Santolaria et al. 2009). No
use of portable CMMs in construction and joinery-
production contexts has been identified.

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research is limited, but some research that quantitatively
investigates the accuracy of laser-scanner data finds that
mixed pixel removal can cause significant measurement
errors (Tang et al. 2009). Further, it found that laser-scanner
resolution, distance to object, object color, object radius,
and laser-beam intensity are the five variables contributing
to the most to the measurement error (Shen et al. 2013). Little
focus is on tolerances and on lowering the uncertainty of
scanning to achieve dimensional reliability and information
needed in terms of “Productive Metrology” (Kunzmann et al.
2005). A guide for planning 3-D imaging of built
environments specifies general levels of accuracy and levels
of detail (US General Services Administration 2009), but
there are not any definitions of accuracy needed for different
guilds of the construction work. Since the guild of supplying
joinery products is even less represented in the research
literature, this is also valid for that guild. Therefore, much of
the needed measurement accuracy is situation dependent,
and this impedes classification of suitable products for as-
built measuring at construction sites.

Methods

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photographs, and documents was the basis for analysis.
Cartesian space the X-direction represents the wire-extraction position, the Y-direction represents the horizontal sensor position, and the Z-direction represents the vertical sensor position.

Horizontal and vertical sensor test setup.—For the horizontal sensor accuracy testing, the PWCMM was positioned horizontally on the floor with four reference targets positioned along the measurement arm’s 402° horizontal range (Fig. 3A). The reference targets were positioned with 90° intervals from the beginning to the end of the horizontal range at −180°, −90°, 0°, 90°, and 180° positions. The 180° position reused the same reference target positions as the −180° recording. Each position has a wire extraction of 700 mm from the machine origin. In the Cartesian space the X-direction goes along with the axis between the 180° and 0° positions, the Y-direction goes along the axis between 0° and 90° positions, and the Z-direction goes out from the image plane.

For the vertical-sensor accuracy testing, the PWCMM was positioned vertically on the floor. Four reference targets were closely positioned on the floor allowing a vertical motion of the measurement arm at −20°, 10°, 40°, and 70° positions along its 104° range (Fig. 3B). Each position has a wire extraction of 300 mm from the machine origin. The horizontal motion of the measurement arm was not fixed; the horizontal positions were 93°, 92°, 93°, and 130°. In the Cartesian space the X-direction goes along with the axis between the −20° and 70° positions, the Y-direction goes perpendicular to the X-direction in the image plane, and the Z-direction goes out from the image plane.

Responses.—In the test of accuracy of the machine’s three sensors, the variability of measurements from four positions was used. Owing to the recording of the PWCMM positions being made in a Cartesian coordinate system, the data are stored as three numerical values, X, Y, and Z. The coordinate values from the four positions needed to be compared between the measurement positions.

The chosen design for this comparison was to calculate the size of a response vector from the center of gravity for each of the measurement positions. The center of gravity was found by using the mean of each X, Y, and Z coordinate value among the 30 replicates. Equation 1 shows the calculation of the position of gravity, XPG, for the X-coordinate value for one of the four test positions. This was also repeated for the Y- and Z-coordinate values and for each test position. In this way the center of gravity was established at each test position. Then a response vector was calculated as the distance from the center of gravity to each test position.

\[
X_{PG} = \frac{1}{30} \sum X_n
\]
center of gravity for each measurement recording by using Equation 2.

\[ XYZ_{RV} = \sqrt{(X_{RP} - X_{PG})^2 + (Y_{RP} - Y_{PG})^2 + (Z_{RP} - Z_{PG})^2} \]  

(2)

where \( X_{RP}, Y_{RP}, \) and \( Z_{RP} \) are the coordinate values for each measurement recording, which were compared with the center of gravity for each test position. With the center of gravity treated as a reference value, the response vector represents an absolute value of the error of each measurement recording. Now the variability of the random error of the PWCMM can be represented. The response vector \( XYZ_{RV} \) is used for all of the performance evaluations of the PWCMM sensor accuracy.

An analysis of variance (ANOVA) was performed for significance testing of the measurement error contributions of the machine’s three sensors. A Tukey’s pairwise comparison (Tukey 1953) was performed to control whether the measurement error at the tested factor positions differed significantly between each other. It was assumed that if the random error is low, the relative accuracy is high, thus ignoring the systematic error.

Testing of PWCMM leap function

The PWCMM has a function called leap to extend the measuring range by relocating the machine while maintaining measurements before and after relocation in the same coordinate system. Four reference targets are measured before and after machine relocation, and the positions of these are used to calculate the new position of the machine after relocation (Fig. 4).

The PWCMM leap function was tested by measuring an 88-m-long corridor wall with a series of nine machine relocations (leaps). The mismatch error of each leap was tested by measuring the position of two fixed reference targets on the wall before and after each leap (Fig. 4). There was a set of two reference targets for every performed leap along the 88-m distance. The upper wall reference for each set of two wall references was aligned to a horizontal line laser projection from a Leica Lino L2 (Leica Geosystems 2014). The individual leap mismatch error, in size and direction, was measured as the difference in position for each of the two wall references before and after machine relocation. This was compared with the mismatch information displayed by the PWCMM. After each leap, the absolute mismatch error was measured as the distance from the registered position of upper wall reference target to the horizontal laser reference line. The absolute error was measured in a two-dimensional sense because of the absence of a three-dimensional reference. The horizontal accuracy of the Leica Lino L2 line laser is \( \pm 1.5 \text{ mm/5 m} \). Two test runs were performed.

The four cases

Four case studies have been carried out with different levels of complexity. Measurements have been performed with the tested PWCMM, a Proliner 8. A Leica Lino L2 line laser was used to create horizontal or vertical reference lines that were used to control orientation of the Cartesian coordinate system when modeling the measurement data. The measurement data were exported from the PWCMM to Solid Work CAD software, where they were refined into 3-D models.

Case 1 was a room-section contour measured for supplying prefabricated wall and glass partitions including doors to an industrial premise being rebuilt into an office environment. The measurement was performed as two contour measurements where the wall and glass partitions were to be positioned. The two contours were measured separately and aligned manually in CAD software. No leap function was used.

Case 2 involved measuring conference room wall surfaces for an indoor wooden panel system and measuring a series of office contours that will receive prefabricated wall, door, and window partitions, constituting the office rooms against the office corridor. The conference room wall
surfaces were measured by defining the surface planes with three coordinates and then measuring the contours of these wall segments. For the series of offices, the PWCMM’s leap function was used to extend the range in order to measure the series of office booths. Measuring the office’s rectangular contours was done with two coordinate registrations for each side of the contour. Before relocating the machine, four reference targets were registered with the leap function. After relocation, the same reference target positions were registered. This allowed the leap function to calculate the new machine position so as to maintain the new measurements within the original coordinate system.

Case 3 involved measuring a complex-shaped object of large scale, a 12-story staircase, where the joinery-products supplier was to develop, manufacture, and assemble a staircase railing system in solid wood. The inside profiles of all staircase sections were measured as contours of a number of both small and large surface planes. Each of the 12 floors’ staircases was measured separately with a single positioning of the PWCMM. No leap function was used here. For every floor, a horizontal reference laser line was projected against the side of the floor sections of the staircase. Before performing the full measurement, the measurement method was tested by manufacturing and assembling three prototype railing sections based on the PWCMM measurements. After refining the measurement data to a 3-D model, floor-height measurements in the model were compared with manual steel tape measurements and drawing.

Case 4 involved the measurement of a building with complex exterior and internal shapes with curved walls or other than 90° wall–wall alignments. The materials supplied involved shelf systems, clothing wardrobes, reception desks, visitor seating, wall panels, a “hidden” door in line with a wall panel system, postboxes, etc. (Fig. 5). The PWCMM measuring was performed twice with two different methods. The first was a plan projection method, where the floor plane was defined with three coordinates, and then the positions of the walls were measured close to the floor and projected onto the floor plane, from which the wall surfaces then were extruded vertically. In the second surface-measuring method, the machine stylus probe was swept over the wall surfaces to register many coordinates. Then the wall surface planes were defined by averaging the measured coordinates of each wall surface. By this means information on the walls’ vertical alignment was captured. The corners between walls and wall-to-floor were defined as the intersections between the surface planes. In both these measurements the range of the PWCMM was insufficient, and the machine’s leap function was used with one machine relocation. Differently colored models from the two different measurement methods were compared mutually in CAD software. The models were superposed on each other to illustrate the mutual differences. Complementarily, a laser scanning measurement was performed by an external contractor using a Leica Scan Station C10, to which the PWCMM measurements were compared.

**Results**

**PWCMM sensor accuracy**

A 3-D scatterplot for each of the three sensors, the wire-extraction sensor, the horizontal and vertical position sensors, shows how the measurement recordings are distributed around the measurements’ center of gravity (Fig. 6). For the wire-extraction sensor positions, the error spread is ±0.8 mm in the X-direction, ±0.5 mm in the Y-direction, and ±1.9 mm in the Z-direction (Fig. 6A). The error spread for the horizontal sensor positions is ±0.95 mm in the X- and Y-directions and ±0.5 mm in the Z-direction (Fig. 6B). For the vertical sensor, the error spread is equal in all three directions, ±0.25 mm (Fig. 6C). Note that X-, Y-, and Z-directions cannot be compared between the tested sensors owing to different Cartesian orientations in the setup.

The size of the measurement error that can be expected at each PWCMM measurement registration depending on the sensor positions is shown by the confidence interval plots (Fig. 7). The wire-extraction sensor gives absolute errors in the range 0.27 to 0.35 mm at the 100-cm position, and 0.78 to 1.13 mm at the 650-cm range, both with a 95 percent individual confidence (Fig. 7A). The horizontal- and vertical-position sensors show a more constant contribution to the measurement error along their working range (Figs. 7B and 7C). Note that X-, Y-, and Z-directions cannot be compared between the tested vertical sensors owing to different Cartesian orientations in the setup.

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**Figure 5.—Examples of supplied products from Case 4: (A) a floor to ceiling shelf system; (B) a visitors’ seating area with wall-integrated seating; (C) reception desks.**
The measurement error at 280 cm is significantly lower than at 650 cm, but not significantly lower than at the 470-cm position. The errors at 470 and 650 cm do not differ significantly.

**Tested leap-function performance**

Measurements of the 88-m-long corridor with a series of nine PWCMM relocations, or leaps, show that the measured individual mismatch errors for each of the leaps are larger than on the user information given from the machine (Figs. 8A and 8B). The machine’s user information shows mismatch errors in the range of 0.5 to 2 mm (CMM-Info), while the measured mismatch ranges from 0.25 to 6.5 mm (Ref1 and Ref2). The mismatch error has irregular orientations. As the leap series continues, the measured absolute mismatch error is significantly larger than the accumulated individual mismatch errors (Figs. 8C and 8D). Here, the absolute error reaches values of hundreds of millimeters. The absolute error can also change directions (Fig. 8C).

**Case results—Accuracy and usability**

In Table 1 is an overview of accuracy and usability experiences from the four cases presented here.

*Results of Case 1: Factory to office restoration.*—This first case was seen as successful by the joinery-product supplier who used the processed measurement data in the design modeling of their product (Fig. 9). The joinery products were assembled on-site without measurement-related problems. However, some accuracy and usability issues were noticed (Table 1).

*Results of Case 2: New supplier office.*—In the second case the processed measurement model of the conference room showed uncertainties that became evident on studying the corners and the way the measured surfaces met each other. In the six measured corner points, there were mismatches of 0.43, 1.46, 2.36, 3.44, 5.54, and 8.68 mm (Fig. 10). The measurement of the series of offices for glass partitions caused trouble for the PWCMM extension of the measurement range, the leap functionality. In one of three trials with the leap function, the PWCMM responded with mismatch information of 5.2, 1.99, and 42.05 mm after each of the three machine relocations. Finally, in all three trials, the PWCMM could not calculate its new position after relocation. Ultimately, the PWCMM measurement could not contribute to the supply of the series of wall and glass partitions. The summary of case experiences shows some accuracy and usability issues but also advantages over manual measuring techniques (Table 1).

*Results of Case 3: Staircase railing.*—In Case 3, a 12-story staircase was measured with the PWCMM. The process was to measure on site, process the measurement data to a 3-D model, align the product model to the measured model, manufacture the product, and finally assemble it on site (Fig. 11). The first test measuring and measurement-based manufacturing and assembly of prototype railing sections was successful. However, in the following full measuring of the 12-story staircase, a number
of uncertainties of the measurements were revealed when processing the measurement data. For example, some measured surface planes were not parallel or perpendicular to each other, as they were expected to be. These deviations often resulted from one erroneous coordinate registration, or error leveraging, when defining one of the planes in the PWCMM model. Further, small angular deviations of surface planes were found that could easily be thought reliable, since measured objects likely contain small irregularities that owing to leveraging can have a large effect on accuracy. These were recurring problems affecting the measured floor heights and staircase contour size, measures defined in the architectural drawings. Owing to these uncertainties and the fact that processing the 3-D model based on measurement data was time-consuming, the supplier chose to process the full 12-story 3-D model based on architectural drawings.

Floor heights from both the PWCMM model and the steel tape measures were different from the heights specified in the architectural drawings and were also different from each other (Fig. 12). Sometimes the measured floor heights are close to each other, sometimes not, which indicates measurement uncertainties. However, these differences are still within the requirements of the Swedish building code (Hus AMA 1998). The case-experience summary shows many accuracy and usability issues (Table 1).

Results of Case 4: Office reception interiors.—In the fourth case, the two different PWCMM measurement methods—the plan-projection measuring method and the surface-measuring method—gave somewhat different measurement data, while the resulting 3-D models are similar (Fig. 13). Superposing the models from the two measuring methods confirms the similarities (Fig. 14). However, with the example measurements, displayed as A1 to A3 and M1 to M5, and the wall W1, differences between the two models can be distinguished. The wall W1 shows the most visible difference, which is explained by the facts that the
The desired result of testing the PWCMM is that the uncertainties of the as-built geometrical dimensions of the construction site can be reduced to a level that allows joinery-product fitting to move to the digital environment early in the supply process instead of being performed manually at the end of the supply process. This has the potential to vastly improve the efficiency of supplying joinery products to the construction industry. To achieve this, measurement errors on par with tolerances for joinery products (±1 mm), preferably meeting the golden rule of metrology, must be achieved.

### Sensor accuracy

The testing of the three PWCMM sensors shows that the amount of extracted wire is the source of the most significant effect on the size of the PWCMM random error. For the error from wire extraction, the largest error contribution is in the Z-direction (Fig. 6). The error in X- and Y-directions is smaller than the total error of the horizontal sensor. The test setup for testing the wire extraction also involves a vertical movement of the surveyor did not measure it as a curved wall with the surface measuring method and that it was a continuous wall that was not measured in total by either of the two methods.

Table 1 — Case accuracy and usability experiences.

<table>
<thead>
<tr>
<th>Accuracy experiences</th>
<th>Usability experiences</th>
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<tbody>
<tr>
<td>Case 1</td>
<td></td>
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<tr>
<td>• 0.9-mm uncertainties discovered on replicated measurements of a contour line</td>
<td>• Easy to measure the contour line</td>
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<tr>
<td>• Uncertainty whether the contour measurements were correctly positioned</td>
<td>• Line laser projection would have been useful to correctly position the contour measurement</td>
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<tr>
<td>• Corner mismatch of meeting contours due to error leveraging when defining surface planes with three coordinates</td>
<td>• Range was insufficient</td>
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<tr>
<td>• Leap function caused significant mismatch error indications, up to 42 mm</td>
<td>• Successful delivery with good prefabricated fit</td>
</tr>
<tr>
<td>• Comparison to manually performed laser distance meter measurements of room opening gave differences in measures up to 14.58 mm</td>
<td></td>
</tr>
<tr>
<td>• Measuring of opposite walls showed deviations from wall parallelism up to 17.40 mm</td>
<td></td>
</tr>
<tr>
<td>• Small surface planes limit the accuracy of plane definition</td>
<td>Case 2</td>
</tr>
<tr>
<td>• Uncertainties from manual aligning of floor-to-floor models</td>
<td>• Difficulty measuring all positions due to construction-site obstacles, thus affecting practical range</td>
</tr>
<tr>
<td>• Erroneous measurements difficult to notice during measuring</td>
<td>• Errors easily pass undetected during modeling if the intersections of the measured objects are not carefully zoomed</td>
</tr>
<tr>
<td>• Difficult to judge whether measurements are accurate</td>
<td>• Supplier engineer discarded measured data as a result of lack of confidence</td>
</tr>
<tr>
<td>• One floor plane was measured as tilted 0.58° because of a 45-mm height distribution between three measured coordinates</td>
<td>• Machine positioning (horizontal/vertical) affects error sensitivity</td>
</tr>
<tr>
<td>• Floor-height measurement comparison shows differences in results</td>
<td>• Leap function wasn’t feasible for narrow corridor measurements</td>
</tr>
<tr>
<td>• 3-mm deviations caused by PWCMM leap function observed</td>
<td>• PWCMM measurements are relational, giving information on vertical alignment of walls</td>
</tr>
<tr>
<td>• Curved wall measured as flat surface plane due to visually undetected curvature</td>
<td>• Reference line or plane from line laser useful</td>
</tr>
<tr>
<td>• Measuring method used affects accuracy performance</td>
<td>Case 3</td>
</tr>
<tr>
<td>• Corner mismatch of meeting contours due to error leveraging when defining surface planes with three coordinates</td>
<td>• Sufficient measurement data were not practically possible to acquire to process an understandable 3-D model; additional information was added during modeling</td>
</tr>
<tr>
<td>• Leap function caused significant mismatch error indications, up to 42 mm</td>
<td>• Range barely sufficient to measure one floor-to-floor stair section</td>
</tr>
<tr>
<td>• Double curvature on surfaces not detected</td>
<td>• Leap function wasn’t practically feasible</td>
</tr>
<tr>
<td>• Line laser projection would have been useful to correctly position the contour measurement</td>
<td>• Modeling was time consuming</td>
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<tr>
<td>• Measuring method used affects accuracy performance</td>
<td>• Errors small in relation to measured object hardly detectable on PWCMM screen</td>
</tr>
<tr>
<td>• Measuring method used affects accuracy performance</td>
<td>Case 4</td>
</tr>
<tr>
<td>• Line laser projection would have been useful to correctly position the contour measurement</td>
<td>• PWCMM users often do not see the screen when performing measurements</td>
</tr>
<tr>
<td>• Measuring method used affects accuracy performance</td>
<td>Case 4</td>
</tr>
<tr>
<td>• Line laser projection would have been useful to correctly position the contour measurement</td>
<td>• Range was insufficient; one machine relocation was performed</td>
</tr>
<tr>
<td>• Measuring method used affects accuracy performance</td>
<td>• Difficult to capture double curvature of surface planes</td>
</tr>
<tr>
<td>• Measuring method used affects accuracy performance</td>
<td>• Not practically possible to capture all construction-site details and surface curvatures</td>
</tr>
<tr>
<td>• Measuring method used affects accuracy performance</td>
<td>• Difficult to understand captured data on the PWCMM screen</td>
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</tbody>
</table>

Further, an advantage of the surface-measuring method was that it captured the presence of nonvertical walls at the construction site. It can be seen how the surfaces of the superposed models intersect each other, which is because of the presence of nonvertical walls in the model of the surface-measuring method (Fig. 16). This was not captured by the plan-projection measuring method. Again, the case-experience summary shows many accuracy and usability issues (Table 1).
Figure 9.—On-site measuring and measurement data processed into a finished product: (A) measuring the contour, (B) the measured contour, (C) the product computer-aided design model fitted to the measured contour, and (D) the finished product at the construction site.

Figure 10.—Case 2 measurement model with mismatching corners. The magnified corners (A to F) show the gaps between the measured surfaces.
Figure 11.—Measuring, modeling, manufacturing, and assembly of a 12-story stair-railing system: (A) on-site measuring, (B) measurement data processing, (C) measurement 3-D model, (D) test-assembly of prototype, (E) aligned product model and site model, and (F) finished staircase railing on site.

Figure 12.—Portable wire-based coordinate-measuring machine (PWCMM) and steel tape measures of floor heights compared with drawing.
measurement arm, which means different positions in the Z-direction. Therefore, despite a low effect on the measurement error from the vertical sensor, the error contribution is leveraged with the amount of extracted wire from the PWCMM. This shows that the error increases proportionally with the amount of wire extracted from the PWCMM. It is likely that also the error of the horizontal sensor is affected in a similar fashion.

At close range, within 100 cm, the level of accuracy is close to the requirements of the golden rule of metrology and highly interesting for verifying as-built site geometries when supplying joinery products. However, as experienced in the studied cases, the normal situation is that measurements need to be carried out in the outer range of the tested PWCMM. Then the random error can be expected to be 0.78 to 1.13 mm in a single coordinate registration. This would be on a par with the tolerance requirements on the products of the joinery-product supplier.

Analysis of leap function

The results show that using the PWCMM leap function adds uncertainty to the measurements. The mismatch errors displayed on the machine may seem insignificant, but the actually measured mismatches are up to three times larger (Figs. 8A and 8B). Furthermore, the test shows that the absolute mismatch error can increase for every leap, to vast proportions, significantly larger than the accumulated individual mismatch errors. Moreover, the mismatch orientation is irregular. Because of these circumstances, the PWCMM user cannot predict the effects of the mismatch errors when using the leap function for series of leaps.

The case experiences have shown that the 7-m range is often a limitation of the usability of the PWCMM. Both the size of objects and the presence of obstacles make using the leap function necessary. Therefore, the leap function is desirable, but currently the absolute mismatch error increases greatly after a few leaps, which reduces the usability of this function. It should be possible to further develop the leap function by using a method whereby repeated measurement registrations of the reference positions are averaged. If the absolute mismatch could be reduced to a few millimeters after a few leaps, the machine’s usability would be considerably improved with respect to the needs of a joinery-product supplier.

Case analysis

With the purpose of creating representative as-built 3-D models that can be used for digital product-to-room fitting of joinery products, the cases reveal a number of issues with accuracy and usability of 3-D sensing of as-built construction site dimensions with the PWCMM.

Accuracy analysis.—The case experiences have shown measurement errors of considerably higher magnitude than the test of the sensor accuracy reports. Chiefly four factors have been identified that affect measurement accuracy in the studied cases:

- Accuracy of measured coordinates
- Representativeness of chosen coordinates

![Figure 13](https://via.placeholder.com/150)
First, the accuracy of measured coordinates is affected by the distance from the PWCMM to the measured object. When measuring, this distance always varies, and therefore the accuracy varies as well. The results show that errors in the outer range are up to three times larger than at short range. In the cases where the PWCMM often was operating in its outer range, accuracy was lower, but still on par with joinery-product tolerances. Despite this, uncertainties in measurement accuracy of significant magnitude have been experienced when processing measurement data in the studied cases.

Second, a measured coordinate accuracy of about ±1 mm or less puts demands on the representativeness of the measured coordinate position. At a construction site, a contour line or a surface often has irregularities with a magnitude larger than ±1 mm affecting the accuracy of the

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**Figure 14.—** Superposed models from the plan-projection measuring model (gray) and surface measuring model (red) show few visible dissimilarities. The model measures A1 to A3, and M1 to M5 are used to quantify differences between the measurement models.

**Figure 15.—** Differences between the portable wire-based coordinate-measuring machine (PWCMM) measurement methods compared with laser-scanning reference: (A) wall angle differences and (B) length measurement differences.
PWCM measurements. This was experienced in all cases but can be exemplified in Case 2, where corner mismatches were caused by low representativeness and error leverage when defining the surface planes (Fig. 10). Similarly, in Case 3 the uncertainties of the floor heights were affected by this coordinate representativeness issue when defining the floor plane with three coordinates. Therefore, the measured surface planes became skewed.

Third, error leveraging is an error contributor in most PWCM measurements. In the small scale, error leveraging occurs when measuring contours with two coordinate positions at each side and then connecting the contour lines where they intersect. This occurs in almost every PWCM measurement. Another frequent error-leverage situation occurs when defining a surface plane with three coordinates that are not well extended in all Cartesian directions and then performing measurements far outside the area of the surface-defining coordinates. Owing to normal measurement errors, these surface planes get slightly skewed. When the outer contour of that larger surface is thereafter measured and these measurements are projected onto the defined surface plane, the errors from the first defining coordinates are leveraged. This is a source of significant error leverage that was observed in the corner mismatches in Case 2 and floor heights and contour-size uncertainties in Case 3. The uncertainties in Case 3 were smaller than tolerance requirements in the Swedish building codes for floor-plane heights but significant for the fitting of the staircase railing system supplied in this case. The studied cases show that the errors from the less representative coordinate measurements and from error leveraging interact and therefore increase the original error of the PWCM.

Decreasing the sensitivity to error leveraging would be beneficial for PWCM usability. To achieve this, the measuring should be planned to register as many coordinates as possible and average these values when acquiring as-built information from the construction site. The surface-measuring method in Case 4 (Fig. 14) is one example of how to use the power of averaging with the tested PWCM. This method was found more reliable than the plan-measuring method and can therefore increase the accuracy of measuring as-built construction sites with the PWCM. However, because the PWCM data need to be processed in CAD software, the application of an averaging measuring strategy to measure rectangular-shaped objects is limited by the lack of line-fitting operations in CAD software.

Currently most CAD software is not well suited to importing measurement data for which fitting operations are needed, and this affects the usability of the tested PWCM.

Fourth, extending the operative range with the PWCM leap function is a very attractive feature that unfortunately introduces significant errors. The use of the leap function was introduced in Case 2 and Case 3, but prevailing construction-site conditions prevented successful measurement using a series of leaps. In Case 4, the leap function was used successfully. Here, one leap was used, and uncertainties in the range of 3 mm were found. Aside from the size of the error introduced by leaps, the problem is that the direction of introduced error cannot be predicted by the user. By measuring parts of the objects before and after the leap, the orientation of the error can be assessed when modeling the measurement information and possibly compensated for.

A more accurate leap function would require higher PWCM sensor accuracy, or that the method for the leap function be further developed with repeated measurements of the reference targets and averaging of their measured positions were used in the calculation of the PWCM position after the leap.

Furthermore, another factor affecting PWCM measurements is that the as-built environments at construction sites often have undesirable horizontal and vertical surface curvatures. These are often of such magnitude they affect the fitting of joinery products. Even if the accuracy of the tested PWCM were adequate to measure some of these undesirable surface curvatures with an averaging method, the repeating of a mesh measuring strategy would be needed. Here, repeated measurements of a full geometric identification method as presented by Skalski et al. (1998) would be needed. For large-scale objects such as construction sites, such kinds of high-density mesh measurements would be time-consuming with regard to data acquisition and would require complementary equipment showing the mesh pattern. The modeling of such data would require considerable processing time and improved software support. In terms of usability, the tested PWCM with its manual probe positioning would not be appropriate for such high-density measurements.

Owing to the involvement of these factors in the PWCM 3-D sensing, measurement errors significantly larger than the tolerances of joinery products have been experienced in the studied cases. With the difficulties of estimating the size and direction of errors, the reliability of the PWCM measure-
ment based models is not on par with joinery-product tolerances. Hence, the hypothesis of eliminating dimensional uncertainties of as-built construction sites to a level on par with joinery-product tolerances is rejected. Usability analysis.—Three main usability issues have been experienced in the studied cases:

- Range and reach
- Limitations in “picturing” the construction site and its details
- Level of expertise needed to perform accurate measurements
- Processing measurement data to measurable 3-D models

First, the range and reach of the tested PWCMM is unique compared with other equipment on the market. However, in the studied cases, the PWCMM often needed to work in the upper end of the range, or else the range has been insufficient. Furthermore, the measurements need to be in line of sight for the machine wire. Even a small ledge on a surface can be an obstacle to positioning the measurement probe. Therefore, these range and reach limitations often restrict the possibilities of sensing many positions that can increase the level of construction-site detail that can be depicted. In the attempts to overcome these limitations with the leap function, there have been severe accuracy issues. Therefore, limitations in range and reach have been a major usability issue.

Second, limitations in “picturing” the construction site and its details mean that the PWCMM measurements and modeling can only supply a simplified reconstruction of a construction site. This simplification means that spatial information of importance to the joinery-product supplier can still be missing. Experiences from the cases and from the joinery-product suppliers involved are that 3-D models of construction sites are rare. Therefore, the as-built verification cannot be performed using only a few control coordinate positions; the site needs to be depicted and reconstructed into an understandable model. Practically speaking, there are limitations on the level of detail that can be achieved. In Case 3, it wasn’t practically possible to capture measurement information needed to reconstruct an understandable 3-D model. Here, additional information from drawings was added to the model reconstruction. Because of this, the model has limitations in what parts can be used for fitting products to the as-built environment. Therefore, limitations in the ability to depict site details present a severe usability issue.

Third, measuring a construction site with the PWCMM requires a high level of expertise. The case experiences have shown many potential handling errors. There are many details that need to be captured when measuring a construction site. Further, the measurement probe has an offset that the user needs to consider for accurate measurements. Displaying large objects on a small screen makes measurement progress difficult for the user to follow on the PWCMM screen. Therefore, it can be difficult to judge whether enough information is captured until measurement data are processed in CAD software after measuring. The cases have shown many uncertainties that needed consideration when reconstructing a 3-D model from the measurement data. An experience of the construction site and understanding of the measurement process have been essential. Therefore, the reconstruction of measurement data also requires a high level of expertise and is difficult to perform for anyone other than the person who did the original measuring. Consequently, many errors can be introduced without high-level expertise in PWCMM measurement and the reconstruction of measurement data into a 3-D model. This is therefore a critical usability issue, and thus the hypothesis of meeting practical usability needs is rejected.

Conclusions

A portable wire-based coordinate-measuring machine (PWCMM) has been examined in the context of performing as-built dimensional site verification for supplying joinery products to the construction industry. Reliable as-built construction site dimensions in 3-D are a necessity for moving fitting of joinery products to the digital domain and by that means improving the efficiency of the supply process. To achieve this elimination of dimensional uncertainties of as-built construction sites to a level on par with product tolerances is seen as a minimum requirement. The random errors of the PWCMM are close to meeting tolerance requirements for joinery products, and when the objects measured are small, the requirements of the golden rule of metrology are also close to being met.

The studied cases show greater uncertainties in accuracy than the investigation of the random error gives the appearance of. The case analysis shows that practical accuracy is affected by limitations in coordinate representativeness due to the roughness and/or unevenness of construction site surfaces and error leveraging. These accuracy issues can potentially be reduced with an increased possibility of measuring with increased coordinate density and applying averaging of measured coordinates.

Construction site PWCMM measurement often requires the device to work in the upper end of the working range, or beyond, making it necessary to use the leap function, which further increases inaccuracy. This is a zone in which the PWCMM produces its highest level of random error. Further, the construction can only be depicted with a low resolution. Because this depiction is performed manually, the skill of the measurer is crucial to its quality. Automated processing of PWCMM data to 3-D models is hardly possible because of the need for understanding of the measurement data. Additionally, the many uncertainties in resulting models are obstacles to the usability and improved automation of the process of supplying joinery products. Therefore, the hypothesis of eliminating dimensional uncertainties of as-built construction sites with the PWCMM to a level on par with joinery-product tolerances is rejected.

Literature Cited


Anil, E. B., P. Tang, B. Akinci, and D. Huber. 2013. Deviation analysis method for the assessment of the quality of the as-is building information models generated from point cloud data. Automation Constr. 35(0):507–516. DOI:http://dx.doi.org/10.1016/j.autcon.2013.06.003


Three-dimensional, as-built site verification in supplying engineer-to-order joinery products to construction

Authors:
Samuel Forsman, Lars Laitila

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Three-dimensional, as-built site verification in supplying engineer-to-order joinery products to construction

SAMUEL FORSMAN & LARS LAITILA
Wood Science and Engineering, Luleå University of Technology, Skellefteå, Sweden

Abstract
With currently used surveying methods, the on-site assembly of joinery products often consumes half the supplier budget. Due to spatial uncertainties, the manual product-to-room fitting of components is a major consumer of time and labour resources. With reliable as-built construction-site geometrical information, this fitting could be moved to the design stage early in the supplier process. In this study, the currently used manual surveying methods were compared with two different three-dimensional (3-D) sensing surveying methods, a portable wire-bound coordinate measuring machine (CMM) and a laser-scanning machine. The comparison evaluates the applicability of the on-site surveying methods and their potential for improving the current surveying process, moving the product-to-room fitting to the design stage. Results show that currently used manual surveying methods leave uncertainties regarding the dimensions of a construction site and are insufficient for moving the product-to-room fitting to the design stage. CMM surveying has the potential to supply coordinate registrations on a par with desired accuracy requirements, but it has limitations at the practically possible detailing level. Laser scanning seems to be applicable for the surveying for a joinery products supplier, but the accurate and detailed 3-D reconstruction of the point-cloud data is difficult and requires extensive processing. It can be concluded that the concept of digitized measurement of the as-built spatial dimensions of a construction site to enable product-to-room during the design stage has the potential to succeed with currently available digitizing technologies, but that some challenges remain.

Keywords: Automation, construction, craftwork, joinery products, suppliers, industrialization

Introduction
The construction industry is the major customer for most industrial wooden products. Worldwide, the construction industry is one of the most important elements of every economy. Current research places much attention on quality and efficiency issues, supply chain management, management from a general contractor perspective, innovation, lean production and automation. More recently, the climatic impacts of the construction industry have become a significant topic. To deal with these challenges innovation is needed, and this requires effective cooperation, coordination and working relationships across interorganizational borders (Ruten et al. 2009, Ozorhorn et al. 2011), yet there has been little focus on development within the numerous guilds, suppliers and contractors within the construction supply chain.

In the following, we focus on the supply of specifically designed engineer-to-order joinery products, such as entrances, glass partitions, doors, windows, cabinet fittings, stairs, etc. This is involved in most commercial construction and refurbishing projects but is seldom discussed in the construction and wood-related literature.

Joinery product suppliers manufacture product components, package them in the factory and transport them to the construction site where they are assembled. This is, in general, a process with two main parts, an efficient factory production and a less efficient and labour-intensive work at the construction site. The amount of labour-intensive work depends on the level of product prefabrication, and on how well the finished joinery products fit the intended location. Reliable “as-built” spatial data through construction-site verification is crucial for...
the manufacture of joinery products that can be assembled efficiently. Currently, the assembly work often consumes half the joinery product supply budget, and the manual fitting of components consumes much of the assembly work.

Building Information Models (BIM) are increasingly being used in the Architecture, Engineering, and Construction (AEC) domain. These semantically rich 3-D models that store information in a single integrated source, were originally developed to enhance planning, visualization and communication during design, to detect mistakes during construction and to simulate space planning during management (Sacks et al. 2004, Akinci et al. 2006, Eastman 2008, Xiong et al. 2013). “As-designed” or “as-planned” BIMs predominate in the AEC domain. These BIMs may vary significantly from the “as-built” or “as-is” conditions at the facility. These differences have various origins, such as undocumented design changes, inadvertent errors in the construction and subsequent renovations (Xiong et al. 2013). There is therefore a need for BIMs based on “as-built” or “as-is” conditions. Hereafter, we use the terms “as-built” and “as-planned” to distinguish between the two conditions.

The generation and use of as-built geometrical conditions in construction has gained momentum embracing areas such as quality assessment, progress and productivity monitoring, materials tracking and automated routing for construction vehicles, etc. (Tang et al. 2009, Huber et al. 2011, Turkan et al. 2012, Anil et al. 2013, Argüelles-Fraga et al. 2013, Kim et al. 2013, Xiong et al. 2013, Boscè and Guenet 2014, Boscè et al. 2015). Much focus is on the automation of the process to achieve the as-built geometries from 3-D sensing technologies (Anil et al. 2013, Kim et al. 2013, Xiong et al. 2013). In this study, we focus on achieving as-built geometries from construction sites that increase automation in the supply of engineer-to-order joinery products.

Uncertainties in the as-built geometrical information provided by currently used methods have been shown to cause considerable waste in the supply of joinery products: unnecessary transport, motions, waiting, overprocessing, underprocessing and defects (Forsman et al. 2012). Much of this waste can potentially be eliminated through automation based on BIMs with accurate as-built geometries and information about the construction process. Three examples of this are the following: (1) moving the manual fitting at the end of the supply process to the digital environment early in the supply process, which would allow automated product-to-room fitting, and the use of numerically controlled machinery to perform the physical fitting on the product components. (2) Adopted to the size limitations of transport routes on-site, the design of parcels in the digital domain can be performed to optimize on-site delivery; (3) synchronizing the supply process with the construction process by ensuring that the adjacent environment has been prepared for the assembly of the joinery products.

In this paper the current manual surveying methods for achieving as-built geometries from a construction site was compared with two three-dimensional (3-D) sensing technologies in a perspective of increasing the efficiency of supplying joinery products by moving the product fitting to the digital domain. The purpose was to assess the applicability of this surveying process and whether the achieved as-built information can enhance process rationalization within this construction field.

Method
This is a case study of surveying methods for the on-site collection of as-built geometrical data. Currently used manual surveying methods by two joinery-product suppliers were compared with surveying methods using 3-D sensing technology. The 3-D sensing technology was represented by a Proliner 8 coordinate measuring machine (CMM) and a Leica Scan Station C10 laser-scanning machine (Leica 2014, Prodím 2014). In this case, two joinery-products suppliers were contracted to supply interior fittings for an office building. The office-building plan has a complex outer and inner shape with curved walls and walls that are not perpendicular to each other (Figure 1). The building has geometries that the suppliers consider to be more difficult to depict than an average project using currently available manual surveying methods.

Frame of analysis
The 3-D sensing methods were analysed with respect to their applicability to the joinery-product supply process and with respect to possible improvements in the current surveying process. The surveying data were also analysed with respect to increasing automation within the supply process, primarily by moving the current manual product fitting during assembly at the end of the supply process to the digital environment early in the design process. The following criteria have been used:

1. Improvement in current surveying.
2. Applicability, i.e. possibilities in adapting the technology to the joinery-product supplier process, considering aspects such as:
   a) Information quality
   b) Measurement range
3-D as-built site verification in construction

3. Potential for automatic product-to-room fitting
   a) Model accuracy
   b) Model details
   c) Surface reconstruction

Data collection

The measured region consisted of two parts, the reception area and the cloakroom (Figure 1). Three different methods of collecting data to describe the as-built spatial geometries have been used:

   The manual surveying was performed by the joinery-products supplier, with the help of tape measures, laser distance meters, spirit levels and straight-edge bars, and the methods were studied through direct observations, recorded interviews and a check on the documentation. The observations were documented through notes and photographs.

2. CMM measurements, with a Proliner 8 CMM.
   The CMM is a portable, wire-bound CMM. Coordinates are recorded by a remote control when a hand-held stylus probe, wire-bound to the machine, is positioned on an object. The CMM measurements and data processing were performed by the authors giving full access to the data and experiences. The studied areas (Figure 1) were measured in two separate coordinate systems due to the limited range of the CMM and limitations in the range-extending functionality of the CMM. The reception area was measured using the range-extending feature to achieve one CMM relocation with measurements within the same coordinate system. Two different measurement strategies were used to capture the spatial data of the construction site: (1) a plan projection and a surface plane-averaging method. In the first method, the floor plan is defined with three coordinates and the positions of the walls are measured close to the floor by recording two coordinates for each straight wall line. The measured wall lines are then projected onto the floor plane. The second method aims to capture as many coordinates as is practically possible for every measured floor and wall surface plane. The CMM then defines a plane by averaging the coordinates. Both strategies generate surfaces/planes that are flat, although the surface plane-averaging method evens out for any surface unevenness and is thus less sensitive to surface imperfections. The reception area was measured using both measurement strategies, and the cloakroom was measured using the plane projection method.
For curved walls, the surface plane–averaging method was not applicable. In this case, many coordinates were recorded continuously along the wall, and coordinates were registered at fixed time intervals, about three registrations per second. Within the CMM, these coordinates were projected onto the floor plane and a curve-fitting algorithm calculated a curve shape from these coordinates.

3. Laser-scanning measurements, with a Leica Scan Station C10 laser-scanning machine. The laser scanning was performed by a professional who provided the authors with a finished 3-D model as well as the merged point-cloud data from the four scanning positions. The resolution of the scanner was set to medium, which means that coordinates are captured for each 900 microradians in the $x$ and $y$ directions. This is a commonly used resolution for scanning construction-site objects. The 3-D model and the point cloud share the same base coordinate systems and they are therefore fully superposed and can be mutually compared. This was used by the authors to qualitatively compare the 3-D model with the information available in the point-cloud data and to analyse the differences in shape and level of detail provided by the 3-D model and the point-cloud data. The point cloud was subjected to a qualitative study with respect to coordinate density in different regions of the point cloud and with different angles between the laser beam and the captured geometry, noise depth, identification of details and detail boundaries, etc. Surface irregularities have been studied using deviation maps where the point-cloud data were compared with best-fit planes and surfaces.

Results and analysis

Currently used manual surveying methods

The surveying process started with the production engineer deciding which dimensional measures to record, depending on the type of product to be supplied. This work was based on the descriptive documents from the architect and performed by different persons in the supplier organization, at different occasions.

From a predetermined list of measurements, the surveyor worked to determine wall placements, diagonals in the rooms and the positions of pillars and doorways. Most of the measurements were made at the floor level. The measurements made were noted on drawing printouts and were subsequently used as the basis for the production preparations. It was observed in the notes on the drawing printouts that not all the predetermined dimensions were measured. The notes on the drawing needed to be interpreted and required verbal communication between the surveyor and the production engineer.

To survey the complex parts of the rooms with non-perpendicular walls or curved wall segments, two methods were used. Firstly, the lengths of the walls and the diagonals were measured to determine the correct wall angles (Figure 2a), and secondly, the shape of the curved wall segment was determined by measuring the length with a tape measure and then pressing an E-shaped gauge against the wall and noting the distance from the gauge to the wall (Figure 2b). These data enabled the wall’s horizontal radius and the sector angle of each curved surface segment to be calculated with the help of the intersecting chord theorem. The calculated radii of the four segments (a–d) were as follows: 1,768 mm, 2,282 mm, 2,282 mm, and 1,818 mm. The
corresponding sector angles were 23.9°, 18.5°, 18.5°, and 23.2°. These radii, sector angles, and the measured length of the curved wall, were used manually to produce a CAD model of the surveyed room. This data processing required meticulous attention to avoid introducing errors into the model.

There were many situations leading to uncertainties in the accuracy of the readings. Examples of such situations are as follows: (1) measurements inside corners with a tape measure due to uncertain start and end positions. (2) Determining the position of a free-standing pillar with a tape measure. (3) Measuring diagonals between corners with a laser distance meter due to difficulties in positioning the laser beam exactly at the corner. (4) Room contour differences in vertical alignment, the models intersect and the differently coloured models do not follow each other vertically. The plane-projection method assumes that the walls are vertical, while the surface plane–averaging method gives information about their vertical alignment, and it is evident that the as-built walls were not perfectly vertically aligned.

Applying the frame of analysis to the CMM measurements reveals:

1. The analysis showed that the currently used manual surveying methods can be improved. The CMM method gives highly accurate relational data in a coordinate system, and many uncertainties in the manual surveying method...
can be avoided or reduced. The processing of data to a model was easier than in the manual surveying and errors in this process were therefore reduced.

2. Concerning applicability it was found that:
   a) Information quality.
   The information obtained with CMM can produce only a simplified reproduction of the construction site. For practical reasons, many site details were never captured, and this introduces uncertainties in the site reproduction and the practical versatility of the model.
   b) Measurement range.
   The range limitations and the need for free passage of the wire-bound sensor probe affected the applicability in this case. The fact that the use of the range-extending feature introduces an uncertainty of several millimetres with just one machine relocation was a disturbance.

Figure 3. (a) CMM measurement of cloakroom, (b) processed 3-D model of cloakroom, (c) CMM measurement of reception area, (d) processed 3-D model of reception area.

Figure 4. CMM data for curved wall. (a) Raw data for curved wall, (b) fitted curve from CMM.
c) Portability.

The CMM was easy to handle but on-site measurements should preferably be supported by processing data on-site. This can be a portability issue since interpreting on a small screen the information from large objects measured in several directions is difficult. Large screens are preferable to increase comprehension when processing the measurement data.

d) Reconstructing 3-D geometries.

The tested CMM plane-projection method resembles manual surveying and yields a two-dimensional (2-D) plan view of the construction site, which means that a considerable amount of spatial information is never captured, and making a 3-D model from such information involves vast simplifications. The surface plane-averaging method was also used to capture information about the vertical and horizontal alignment of the measured surface planes. This provides better information than the plane-projection method, but surface roughness or double curvature is not recorded by either of the methods. The experience with the curved wall shows that curved profiles obtained with the aid of the built-in curve-fitting function of the CMM has the potential to yield an accurate as-built reproduction. The capture of 3-D information is mostly a practical issue, since it is possible to record extrusive measurements on all surfaces.

e) Efficiency in measurement and data processing.

The captured CMM data consist of lines and curves from selected positions at the construction site. This means that the information needs to be interpreted by the user when making measurements and when processing the data. The difficulties in comprehending the data on the CMM screen mean that it is uncertain whether the information necessary for the intended site reproduction has been obtained.

f) Quality improvements communication.

A 3-D model is generated from measurement data more easily than from manual surveying, and there is an improvement in quality in communicating a 3-D model instead of measurement notes on a 2-D printout.

3. The potential for automatically performed product-to-room fitting was:

a) Model accuracy.

Joinery products have in general narrower tolerances than is used in construction work and should be in millimetres range. Most of the individual CMM coordinate data meet this demand, but it may be difficult to meet these tolerance demands in the model resulting from the CMM measurements.

b) Model detailing.

At the construction site, it is practically impossible to capture a lot of detail using the CMM method, and the 3-D models generated may lack details of importance to the joinery-product supplier when digitally fitting products to the spatial data.

c) Surface reconstruction.

In practice, the CMM cannot measure every square millimetre of the construction-site surfaces. This affects the potential for
automatic product-to-room fitting already in the production stage. The simplified construction-site reproduction limits the practical usefulness of the generated 3-D model for digital product-to-room fitting and the subsequent fitting of the physical product using numerically controlled machines.

**Laser scanning**

It was considered that laser-scanning measurements at four scanning positions were required to describe the built area of interest (Figure 6). The resulting point-cloud data consisted of 45 million coordinate positions (1.8 GB). This means that the scanner captures a high density of coordinates describing the surfaces of the measured region. The point-cloud density on the floor decreases with increasing distance from the scan position and there is a region around each scan position where the scanner cannot record any coordinates (Figure 6).

The point-cloud data captured hold a vast amount of detailed information about the on-site geometry, but there is no semantic information, and the point-cloud data must therefore be interpreted. Current research has shown that this scan-to-BIM process can be carried out automatically but it is currently usually a manual operation that is labour-intensive and error-prone (Xiong et al. 2013). Manual processing of the point-cloud data to the 3-D model provided by the professional service provider was used in this case. Examples of how the point-cloud data can be processed and issues affecting the accuracy of the final 3-D model are given in the following.

The point-cloud data from the scanning are shown in the imaging software from an outside view; within the point cloud there are many places where obstacles occlude regions of interest. Due to the lack of semantic information, details inside the point cloud need to be selected to show a given model object. This leads to borderline-distinguishing difficulties. For example, to increase the visibility of details, the ceiling coordinates needed to be removed. This information could not, however, be removed without the risk of removing information about the border between the ceiling and the walls.

There are also difficulties in distinguishing borders in the case of seemingly detailed information captured on-site, e.g. skirting boards, cable channels, window trimmings and ledges (Figure 7a, 7b and 7c). There was a lack of information on surfaces parallel to the laser beam, and this limits the level of detail (Figure 7b). Zooming-in reveals that corners are not sharp since no coordinates...
are present exactly at the surface boundaries (Figure 7c).

The 3-D model from the professional service provider gives much of the information needed for a joinery-product supplier, e.g. the geometry of the room for the products to be supplied with details standing out from the wall and floor surfaces. The point-cloud-based 3-D model contains details such as pillars, metal sheet sleepers, skirting boards and glass partitions (Figure 8a), and this appears to be reliable information. When the point-cloud data were superposed onto the 3-D model, the first impression was that the fit was good and that details in the point cloud were present in the 3-D model (Figure 8b). A closer study reveals, however, that details are missing and that the model walls are considerably higher than the point cloud and the real walls. Due to gaps in the inner ceiling, the height of the ceiling was inaccurately interpreted from the point-cloud data.

Zooming in to details of the superposed point-cloud data confirms that details present in the point cloud are missing in the 3-D model, for example skirting boards and cable channels (Figure 9a, 9b). The presence of the cable channel was not noticed by the joinery-product supplier who thus encountered problems during the on-site assembly of a shelf system covering an entire wall side.

Another issue noticed with the 3-D model from the professional service provider was that the point-cloud intersects wall surfaces of the 3-D model (Figure 9c). This indicates that the 3-D model does not consider the actual on-site wall inclination.

Further investigation of the inclination of the wall in the 3-D model reveals local discrepancies of up to 22 mm between the point cloud and the 3-D model of the curved wall (Figure 10a). This indicates problems in fitting non-regular surface topologies. This is a region with difficulties that is also reflected in the literature where most point-cloud processing assumes flat surfaces or shape primitives that the point-cloud data are fitted against, and topological surface errors are not detected (Anil et al. 2013, Xiong et al. 2013, Bosché and Guenet 2014). A best-fit approach to the point-cloud data representing the curved wall gave a reconstruction of the curved wall surface with a much better fit (Figure 10b). However, modelling all surfaces as best-fit surfaces involves difficulties in defining the corners between the best-fit surfaces. Due to these surface representation issues, it is unclear how a scan-to-BIM service provider can process the point-cloud data.
and how limitations in this process affect the geometrical accuracy of the 3-D model.

Topological surface irregularities frequently occur in on-site surfaces. This is information that can be detected in the point-cloud data. This is exemplified in an analysis of floor and wall point-cloud data using best-fit planes and colour-coded deviation maps identifying topological surface irregularities (Figure 11a, 11b). These show topological surface irregularities approximately ±12 mm in size on the floor surface (Figure 11a) and approximately ±13 mm in size on the wall surface (Figure 11b). It can be seen that the positions of the wall studs behind the gypsum boards cause vertical boundaries in the deviation map and that there are significant double curvatures present in the middle of the wall section.

Analyses with reflection maps of the 3-D model from the professional scan-to-BIM service provider shows that all surfaces such as walls, floors and ceilings are reconstructed as planar surfaces, and the curved wall was reconstructed as narrow planar sections, i.e. the 3-D model wall surfaces were reconstructed as best-fit planes that capture the wall inclination, but not the curvature of the walls. The topological surface information from the point-cloud data was thus filtered out in the scan-to-BIM processing.

Applying the frame of analysis to the results of the scanning measurements reveals:

1. Improvements to currently used manual surveying methods.

The laser scanning captures many details of a construction site with an accuracy down to a few millimetres, and topological irregularities in on-site surfaces can be seen in the scanner point-cloud data. Processing the scan information has the potential to yield in a 3-D model
that can be used for measuring within the model. Many of the uncertainties associated with the manual survey can be avoided or reduced, although uncertainties remain.

2. Applicability, i.e. possibilities of adapting the technology to the joinery-product supplier process. This concerns issues such as:

a) Information quality.
   The scanning captures many details and fairly detailed construction-site models can be reproduced, but reconstructing all the details in a model is a time-consuming task with the risk of introducing errors, which reduce the reliability of the model.

b) Measurement range.
   The range of the scanner is not considered to be a limitation for most joinery-product supplier projects. The need for free passage of the laser beam is the greatest concern due to occlusion caused by obstacles in the laser beam. This problem can be overcome by using many scanning positions but there is some loss of accuracy when the point clouds from many scan positions are merged.

c) Portability.
   Physically, the scanner, tripod and targets are portable. When travelling by air or other commuting transportation mean, they can be fairly awkward, especially if sphere targets are used. For the joinery-product supplier, these are not severe limitations, but the results show that scanning a relatively small construction site with a medium scan resolution generates vast quantities of data. To process such amounts of data on the construction site on a laptop is not easy, and there are difficulties in interpreting the data with the limited size of a laptop screen. Transporting the data to a point-cloud processor while the surveyor remains on the site is also challenging due the difficulties in transferring such amounts of data without physically moving a device with the data. The vast amount of data from the laser scanning is therefore seen as a portability problem, which also affects how soon the data can be processed.

d) Reconstructing 3-D geometries for measurement purposes.
   The laser scan-data contain much information that can be used by a joinery-products supplier to reduce typical uncertainties in the spatial dimensions on the construction site. The large amount of detail present in the point cloud need to be taken into account when the point-cloud data are processed into a 3-D model. Analyses of the 3-D model in this study showed examples of missing details that are present in the point cloud. It was also seen that the fit to the point-cloud data can be affected by decisions made in the point-cloud processing, leading to severe accuracy problems in the reconstructed model (Figure 10a). Selecting the correct coordinates in the point-cloud data to represent the intended surface of the scanned object is another difficulty. On small detailed surfaces and surfaces almost parallel to the laser beam, the number of coordinates can be limited so that, determining boundaries between surfaces and reconstructing them can introduce uncertainties to the reconstructed model.

e) Efficiency in performing measurements and the necessary data processing.
   The laser scanning in this study was performed in less than one hour, which from a joinery-product supplier’s viewpoint is an efficient way of performing on-site surveying. However, processing the point-cloud...
data into 3-D models is more difficult and requires special competence. The supplier has a short time frame between scanning the construction site and delivery of the manufactured products. To use the processed 3-D model for the joinery products, the point-cloud processing needs to be finished soon after the scanning. Many joinery-product suppliers are small-sized enterprises with limited engineering competence and capacity. 3-D modelling is often used by these companies, but the maturity is limited. In such a perspective, the high-level processing of point-cloud data into accurate 3-D models in a short time is a challenge. In addition, the investment in equipment, software and competence needed to process scanned data can be a heavy burden for these companies. A professional supplier of this service would therefore be preferable; but control of the accuracy of the point-cloud data processing is of vital importance since the effects for the joinery product can be substantial if the processed model does not meet agreed accuracy tolerances.

f) Quality improvements in project information communication.

The relative ease of the surveying and gathering the 3-D information in the more detailed model from the scanning are obvious improvements compared to the traditional manual survey. With this model, some of the mistakes made in the studied case would probably have been avoided.


a) Model accuracy.

The joinery-product supplier says that if the as-built dimensions were similar to these in the original documents, in millimetres, this would allow a higher level of prefabrication, where the product-to-room fitting can be carried out already during the design of the product components. The point-cloud data from the laser scanning contains much construction-site details and 3-D information, but also much noise and gaps in the point cloud. The point cloud has a noise depth of several millimetres, and the accuracy was therefore dependent on averaging the point-cloud coordinates to reveal the true position of a detail or a surface. The point-cloud coordinate density has also been shown to vary depending on how the surface relates to the scanner laser beam and decreases greatly with increasing angle of incidence of the laser beam. This together with an increasing beam footprint enhances the inaccuracy of the coordinate positions with increasing angle of incidence (Argüelles-Fraga et al. 2013) and leads to local variations in coordinate density and hence local variations in measurement accuracy. The difficulty in distinguishing the borderline affects the accuracy of the reconstructed model negatively. Surfaces are often reconstructed as planes ignoring any topological surface irregularities. This decreases the borderline difficulties since the intersection between surface planes can define the corners. The opposite occurs for reconstruction of surfaces with topological irregularities. These accuracy problems mean that it is still difficult to meet the tolerances needed by the of joinery-product suppliers even with laser-scanning technology.

b) Model detailing.

Laser scanning has the potential to capture most of the information required by the joinery-product supplier; the challenge is to retain the information through the scan-to-BIM processing. Current research into automated scan-to-BIM processing uses context-based modelling for object recognition, but it does not work on small details in large-scale contexts (Xiong et al. 2013). This is mainly a manual process that is work intensive with many borderline-distinguishing uncertainties. This is reflected in the professionally provided 3-D model, in that details are missing that were present in the point cloud (Figure 9a, b) and in the way surface boundaries are misinterpreted (Figure 8b).

c) Surface reconstruction.

The point-cloud data contain information about construction-site surface irregularities (Figure 11). In the professionally provided 3-D model, wall and floor surfaces were constructed as planes and do not consider any surface curvature. The results also show that the surface of the curved wall is described much better by a polynomial best-fit surface and that the difference between the provided model and a best-fit surface is considerable (Figure 10b). It is therefore clear that the reconstruction of the point-cloud data can lead to inaccuracy in the reconstructed model and make digital product-to-room fitting difficult as well as the subsequent fitting of the physical product using numerically controlled machines.
Comparison between the measurement techniques studied

One part of the measured region, the cloakroom, was selected due to the presence of both non-perpendicular and curved wall sections. Since the manual survey by the joinery-product supplier captures only 2-D information, a 2-D model was made with data from each of the three surveying methods for comparison. When these models are superposed with each other, some differences are evident (Figure 12). The manual survey model clearly differs in shape from the CMM and laser-scanning models. With the chosen superposition fix point, it is seen that the curved wall D has a different radius in the manual survey model and that this skews the shape of the model. Further simplifications in the manual survey model lead to severe inaccuracy problems, for example: (1) there is a 44 mm difference between the model curves for the manual survey and laser scan model for one wall with radius. (2) A wall simplification leads to a 101 mm difference between the two model curves.

The measures A–H in Figure 12 used in the manual survey to define the room contour are the basis for a quantitative comparison of the four models, Table I. The greatest deviation of 43 mm (Measure B) was found between the best-fit model and the manual measurements, compared to the greatest difference of 13 mm found between the three models based on the digital measurement methods (Measure D). The greatest deviation was 11 mm for measures A–H between the CMM model and best-fit model. Between the 3-D model and the best-fit model, both created from the laser-scan data, the greatest deviation was 13 mm.

The mean absolute deviations between all models for measures A–H are given in Table II as an illustration of their mutual measurement precision. This shows that the greatest deviations are between the manual model and the three other models, and the manual survey therefore probably had the lowest measurement accuracy. Among the three 3-D sensing models, the CMM model and the best-fit laser scan model are closer than the two models based on the same laser-scan data. This emphasizes the importance of the processing of the point-cloud data in achieving an accurate 3-D model.

The comparison among the three surveying methods shows there are large differences between the model based on the manual survey and the models from the 3-D sensing methods and that significant differences were found among the 3-D sensing methods.

![Figure 12. Cloakroom 2-D contour defined by: (1) the manual surveying model compared to: (2) CMM model, (3) professionally provided laser scan 3-D model and (4) best-fit laser scan model.](image)

Table I. Comparison between models of measures defined in manual surveying.

<table>
<thead>
<tr>
<th>Measure A–H</th>
<th>Manual survey</th>
<th>CMM 3-D model</th>
<th>Provided 3-D model (laser scanning data)</th>
<th>Best-fit planes model (laser scanning data)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (mm)</td>
<td>6,900</td>
<td>6,800</td>
<td>6,400</td>
<td>6,700</td>
</tr>
<tr>
<td>B (mm)</td>
<td>9,190</td>
<td>9,800</td>
<td>9,350</td>
<td>9,672</td>
</tr>
<tr>
<td>C (mm)</td>
<td>9,400</td>
<td>2,950</td>
<td>2,416</td>
<td>2,416</td>
</tr>
<tr>
<td>D (mm)</td>
<td>6,383</td>
<td>6,383</td>
<td>5,900</td>
<td>5,900</td>
</tr>
<tr>
<td>E (mm)</td>
<td>2,416</td>
<td>+7</td>
<td>+4</td>
<td>+3</td>
</tr>
<tr>
<td>F (mm)</td>
<td>9,672</td>
<td>+41</td>
<td>+32</td>
<td>+36</td>
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<tr>
<td>G (mm)</td>
<td>1,956</td>
<td>‒15</td>
<td>‒10</td>
<td>‒7</td>
</tr>
<tr>
<td>H (mm)</td>
<td>1,056</td>
<td>‒15</td>
<td>‒7</td>
<td>‒5</td>
</tr>
</tbody>
</table>

Differences for measures A–H (Figure 12) between manual surveying, CMM data and laser scan data models is ranging from ‒41 to +23 mm.
models, Table II. The differences between the professionally provided 3-D model and the best-fit surface model indicate that simplifications were made that affected the accuracy of the 3-D model. Such simplifications relate to the presence of topological surface irregularities and of non-vertical walls that are not adequately considered in the professionally provided 3-D model.

Taking into consideration that the best-fit planes model contains more of the 3-D information from the room, this is the most accurate model in the comparison. The CMM model and the best-fit plane models are the most similar to each other. The differences between the manual survey and the best-fit model show that the accuracy of the manual measurements is insufficient to give adequate product fitting during the design and manufacturing of the joinery products. The CMM procedure is on par with the best-fit planes model, but is sensitive to subjective factors and does not adequately capture 3-D irregularities in the construction-site surfaces. A hybrid solution combining the CMM and laser scan data would be an option that possibly could strengthen the measurement performance. However, this would require a method to combine the coordinate system from the two separate methods, which is likely to introduce an error that is difficult to assess. The laser-scan-based 3-D model from a professional provider has shown that the processing of the point-cloud information has a considerable effect on the accuracy of the generated 3-D model. Therefore, tolerance requirements need to be considered if the joinery-product suppliers contract with external providers to provide them with laser-scan survey and point-cloud processing services.

### Conclusions

The study shows clearly that the currently used manual surveying methods leave uncertainties regarding the spatial dimensions of a construction site. This limits the possibility of reducing the time and resources needed to perform on-site assembly of joinery products by moving the on-site product-to-room fitting to the digital domain during design.

The CMM has the potential to supply coordinate registrations on par with the desired accuracy requirements for higher level of prefabrication. However, it is only possible to obtain information for a simplified reproduction of a construction site, and this limits the possibilities for digital product-to-room fitting of joinery products. CMM surveying cannot provide sufficiently accurate spatial information to allow full product fitting during the design of joinery products. Laser-scan surveying has the potential to capture most of the relevant details needed for a joinery-product supplier, but the challenge is to retain the information through the scan-to-BIM processing. The time and resources needed for point-cloud processing can be an issue from a joinery-products supplier’s perspective, due to the short time frame between access to the construction site and the date of delivery of the manufactured products.

The frequent presence of topological surface irregularities combined with point-cloud noise depth and point-cloud density variations make it difficult to achieve measurement accuracy on par with tolerance demands on joinery products. Laser scanning seems to be applicable for the surveying process of a joinery-products supplier, but challenges remain with the level of detail and accuracy to enable product-to-room fitting of joinery products in the digital domain during design.

### Disclosure statement

No potential conflict of interest was reported by the authors.

### ORCID

Samuel Forsman [http://orcid.org/0000-0002-7380-2499](http://orcid.org/0000-0002-7380-2499)

### References


