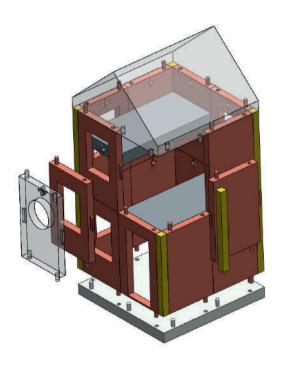
LICENTIATE THESIS

Configuration of Modularised Building Systems



Patrik Jensen





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CONFIGURATION OF MODULARISED BUILDING SYSTEMS

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Luleå, May 2010

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"there is nothing wrong with change, if it just goes in the right direction"
Winston Churchill
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Preface

As the statement explains; change is of nothing bad, it helps us want to learn more. This thesis concludes the joint venture between Tyréns AB and Luleå University of Technology, and somewhere there between myself. Over the last three years I have been challenged to wear two vastly but complimentary hats; one academic, the other as a consultant. In the academic world the focus was education while as a consultant the focus was business. My fellow Ph.D. students called me "Structural phone engineer" because I was always on my cell phone conducting business while studying.

I would like to express my deepest gratitude to my Professor Thomas Olofsson for always pushing me in the right direction and never stop surprising me with your knowledge. Docent Helena Johnsson, you always have a clear and straight forward approach how to tackle the academic. Also the true visionary Vice President Tomas Alsmarker is acknowledged, this journey couldn't have started without you. My colleagues and friends at Tyréns, LTU and Ph.D. students at the Lean Wood Engineering program are truly appreciated, especially Linus Malmgren and Emile Hamon my former colleges at Tyréns.

A special thanks to Tyréns AB for financing the project.

Finally I would like to thank my family and wonderful wife Lina.

You are the sunshine of my life,

Patrik Jensen

Stockholm, May 2010

Abstract

Swedish building industry is mainly project-oriented where the design process is sequential involving various disciplines separated both in time and space. During the last decades the industry has been criticised and accused of having problems with quality and low productivity. One cause is believed to be deficiencies in information transfer between different functional teams in the project organisation. A more product-oriented approach has been proposed by some as one solution that can improve quality and productivity. Several construction companies have started to develop platforms consisting of standardized technical solutions and processes that can be adapted and used in specific projects. However, the current practice of involved disciplines need to adapt to new methods and processes and the question is; Is it possible to apply principles based on mass customisation in the one-of-a kind project dominated construction industry?

In the shift to mass customization, the manufacturing industry is developing product platforms from which customized products can be configured in a so called configuration process. A product platform in the manufacturing industry consists of modules that can be combined into customized products using a configuration system. Modularization is the method used to organize the components of a product family with the aim to simplify and minimize the number of component variants to improve customization without compromising the productivity of the manufacturing process. Erixon (1998) defines modularization as; "Decomposition of a product into building blocks (modules) with specified interfaces, driven by company specific reasons".

The aim of the thesis is to study and propose solutions of the integration between architectural design, engineering and production using mass

customisation principles without changing the traditional structure of the AEC industry. The author's background as practising structural design engineer in an AEC consultancy company has made it possible to study, propose and apply methods in two real-life industrial cases and in one development project of a building system for multi-storey wooden houses. The research performed mainly relies on qualitative research methods combined with action research.

The result of the thesis is a configuration demonstration, in which four product views been identified; the customer, the engineering, the production and the assembly view. Constraints and rules of the building system is transferred upstream while design information is transferred downstream the value chain using design automation and design guides embedded in the different disciplines CAD applications. The process has been illustrated for a cut-to-fit configurable wooden slab module in which a design guide is used in the architect tool transferring dimensional information via XML to the knowledge based engineering tool where the detailed design is automated. The result, including shop floor drawings, bill of quantities and CNC files is then used in the prefabrication of the customized floor slab module. The knowledge based engineering tool used in the demonstration is a product configurator integrated into a 3D CAD system mainly used in the mechanical industry.

To implement configuration processes in the construction industry it is evident that constraints and rules of the building system needs to be transferred upstream to disciplines working early in the specification process. Otherwise the risk is high that "ad-hoc" solutions violating the rules of the building system will be transferred downstream to engineering and production causing quality issues and lower productivity as a result. Implementing configuration processes will also require new business models. AEC consultants with competence in engineering and advanced design tools can develop new modularised building systems and configuration tools rather than selling engineering hours in design of specific buildings. This can also foster the development of more open and flexible building systems on the market.

Keywords: Building system, Modularization, Configuration, Parameterization

Sammanfattning

Svensk byggindustri är i huvudsak projektbaserad med en sekventiell projekteringsprocess där olika discipliner är separerade i både tid och rum. Detta arbetssätt har utsatts för hård kritik och blivit beskyllt för att ha låg produktivitetsutveckling med brister i informationsöverföring mellan de olika aktörerna som sedan får stora konsekvenser på byggplatsen. produktorienterat arbetssätt har av vissa ansetts som lösningen som kan förbättra kvaliteten och produktiviteten. Genom att utveckla standardiserade byggsystem kopplat till standardiserade arbetsprocesser skapas en produktiv plattform som sedermera kan utvecklas till att konfigurera projektanpassade byggnader. Med nya arbetssätt kommer dagens aktörer att behöva anpassa sig till nya förhållanden och frågan som uppkommer, är det möjligt att införa industriella konfigureringsmetoder i byggandet? Denna avhandling är inriktad på att studera och föreslå metoder för att modularisera och konfigurera byggsystem med hjälp av IT-verktyg. Metoder som kan ersätta dagens projekteringsprocess med en konfigureringsprocess av utvecklade byggsystem.

Konfigureringsmetodik kan sammanfattas som ett strukturerat arbetssätt att åstadkomma kundanpassning med bibehållen standardisering med avseende på produktion. För att lyckas med kundanpassningen krävs det att produkten är uppbygga kring moduler och att konfigureringsverktyg utvecklas som stödjer byggsystemets möjlighet att kundanpassas. Modularisering är en metod som har använts inom många olika industrier med syftet att förenkla och minimera antalet komponentvarianter med bibehållen möjlighet för kundanpassning och produktionseffektivitet. En parallellisering av produktion ökar samtidigt produktiviteten för själva tillverkningsprocessen. Erixon (1998) sammanfattar Modularisering som; "indelning av produkter till byggblock (moduler) med

specificerade gränssnitt och utvecklade med företagets speciella förutsättningar".

Syftet med avhandlingen är att studera och föreslå lösningar för integration mellan arkitektonisk design, konstruktion och produktion baserade på metoder hämtade ifrån "Mass Customisation" utan att ändra den traditionella strukturen inom byggindustrin. Författaren är verksam som konstruktör i ett konsultföretag som verkar inom dagens projektbaserade byggande, vilket gjort det möjligt att studera, föreslå och tillämpa metoder i två verkliga industriella fall och i ett utvecklingsprojekt av ett byggsystem för flervåningshus trähus. Den forskning som har bedrivits bygger i huvudsak på kvalitativa forskningsmetoder i kombination med aktionsforskning.

Från fallstudierna har ett IT-baserat CAD verktyg tagits fram, där 4 vyer av produkten har definierats; Kund-, Ingenjörs-, Produktions- och Montagevy. Byggsystemets regler kan illustreras i arkitekters IT- verktyg och sedermera överföras till produktions och montagevyn via parametrisering i ingenjörsverktyget. Regler för byggsystemet definieras i ingenjörsvyn och byggsystemets förutsättningar överförs mellan olika aktörer med få dimensionsparametrar via XML-format. IT-verktyg som används inom ingenjörsvyn är hämtade ifrån den fasta industrin som har mer utvecklade funktioner för definiering av parametrar och parmetriseringsfunktioner.

För att konfigureringsmetodiken skall kunna användas inom befintlig byggprocess krävs det att begränsningar för byggsystemet kan överföras till aktörer som verkar tidigt i processen, vilket leder till minskad risk för "ad-hoc" lösningar vid tillverkning av produkten. Ett sådant arbetssätt kräver också att nya affärsmodeller utvecklas i branschen. Aktörer med kunskaper inom IT och CAD har då goda förutsättningar att utveckla och tillhandhålla effektiva konfigurerbara byggsystem. Det skulle också främja utvecklingen av öppna och mer flexibla byggsystem på marknaden.

Nyckelord: Byggsystem, Modularisering, Konfigurering, Parametrisering

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Appended papers

Paper 1:

Jensen, P., Olofsson, T., Sandberg, M., and Malmgren, L., "Reducing complexity of customized prefabricated building through modularisation and IT support" *CIB W78 25th International Conference on Information Technology, Santiago, Chile, 2008.*

Paper 2:

Malmgren, L., Jensen, P., and Olofsson, T., "Product modeling of configurable building systems – a case study" *Submitted December 2009 to Journal of Information Technology in Construction*.

Paper 3:

Jensen, P., Hamon, E., and Olofsson, T., "Product development through lean design and modularisation principles" *Proceedings of the 17th Annual Conference of the International Group for Lean Construction, Taipei, Taiwan 2009.*

Paper 4:

Jensen, P., Olofsson, T., and Johnsson, H., "Configuration through parameterization of building components" *Submitted June 2010 to Journal of Automation in Construction*.

1 INTRODUCTION

1.1 Background

The construction industry in Sweden has been criticized for low productivity compared to other industries, (SOU 2002). A study of seven construction projects showed that a large amount of work on-site is wasted on redoing errors, waiting and disruptions, (Josephson and Saukkoriipi 2005). The "one-of-a-kind" project orientation is seen as one of the main factors responsible for this situation. Most of today's construction projects are structured according to a sequential product development process in which each design activity is separated in time and space. This process is often slow and reflects functional oriented organizations, leading to deficient communication and conflicts between the different functional teams, (Olofsson et al 2007; Gerth 2008). A more industrialized construction process and development of building systems is one of the proposed solutions to restructure the building process and increase the productivity in the construction industry (Lessing 2006; Johnsson et al. 2006).

The industrialised house-building process according Lessing (2006), see figure 1, consists of the development and configuration of a building system. The building system includes both a technical and a process platform. The building system is then configured adapting the developed technical and process solutions to the specific building project. The idea is to continuously improve the building system through lessons learned from configuration and production of individual projects and develop new improved versions. The shift from unique "on-of-a-kind" building projects to a more process and product centric approach is believed to increase the productivity in the industry. However, introducing new way of working will challenge traditional structures and

organisations in the construction industry. Gerth (2008) argues that when moving to an industrialised construction process, the traditional construction company need to reengineer its organisation to suit a more process oriented way of working.

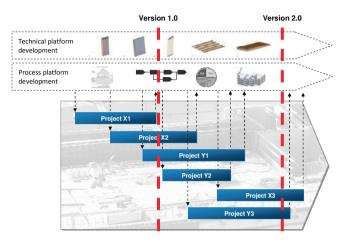


Figure 1: Configuration process in the industrialized house building industry adapted from Lessing (2006).

Subcontractors and suppliers in the Swedish construction industry have during the last decades developed and implemented new subsystems, such as ventilation, bathroom pods and structural frameworks that can be integrated in a parallel sequence of the construction project. (Andersson et al. 2010; Gerth 2008) However, use of configurable buildings requires builders to enter the design phase early in order to be able to consider constraints in the developed building systems (Andersson et al. 2010). Adler (2005) argues that it is essential that the architect is well informed of the system constraints in the design of the building. One obvious approach is to define the final product, leaving the customer to choose from predefined product variants with small possibilities of customization. This approach has been used by many of the companies producing single family houses in Sweden, but also in production of multi-dwellings between 1965 and 1974, when the ambitious housing programme was implemented by the Swedish government with the goal of producing 1 million affordable dwellings. This has resulted in a dramatic increase of prefabricated components and impact on productivity and quality (Bertelsen 2005). However, the focus on mass-production methods resulted in densely built up areas more adapted to large scale production premises than the

living environment for future inhabitants. The demands for standardisation from a production point of view need to be balanced by the demand for customization. Manufacturing industries have developed new methods and design processes combining customers' requirements for customization and at the same time fulfilling the need for standardisation of the production process (Pine 1993; Hvam et al. 2008). Olofsson et al. (2004), Kunz and Fischer (2009) advocates the use of concurrent engineering methods in the construction industry to be able to balance client requirements with engineering and production constraints. Hallman et al. (2008) advocates that construction companies need to adopt product platforms that have a greater customer focus. Adler (2005) argues that's now time for architects to participate in the development of new building systems and technical innovations. Building systems need to evolve from the mass production perspective to include a variety of customisation possibilities.

According to Hvam et al. (2008) there is two central principles of product customization; (1) product ranges should be developed on the basis of modules, and (2) configuration systems should be used to support the customization for different stakeholders and disciplines within the product range. There is a strong need for development of ICT-tools and integrated design and production methods to support the customisation of the final building (Ekholm and Molnár 2009). Support for off-site production of prefabricated components using Computer Numeric Control (CNC) is necessary when factories are installing more and more automated production lines.

So far, design tools in the construction industry have often been developed without the possibility of parameterization or direct connections with Computer Numeric Control (CNC) and do not integrate easily with other tools used by different disciplines (Kunz and Fischer 2009). Samuelson (2003) concludes that construction companies have less developed ICT- experience compared to AEC consultant firms, i.e. the AEC can be key participants in the future development of a customize-to-order configuration process of building systems (Jensen et al, 2010; Ekholm and Molnár 2009).

So the question arises, is it possible to apply configuration principles based on mass customisation in the one-of-a kind project dominated construction industry and if so, what kind of ICT tools are needed to support such a process?

1.2 Aim

Product development and product configuration systems are normally developed to be integrated in sales and design organisation by one company in the manufacturing industry. In construction, the design and production have been separated into vertically integrated design and production speciality disciplines. The aim of this thesis is to study the integration between these disciplines/functions using mass customisation principles without changing the traditional structure between disciplines. The study also aims to investigate the roles and information flow between engineers and architects in a developed configuration process.

1.2.1 Research questions

To reach the aim of this thesis, the research is based on four research questions.

Research question 1

How can modularisation principles be implemented in the design of building systems?

Research question 2

How can information of customer requirements and building systems be managed?

Research question 3

How can configuration be realized in a modularised building system?

Research question 4

How can existing ICT-tools support the configuration of a building system?

1.3 Limitations

The research performed in this thesis is based on the assumption of an industrialized building process using a defined building system. The possible effects of increased productivity are not studied. The research focus is the ICT support systems for the configuration of modularised building system and the effect of such a process on the different disciplines working in the construction industry. Also the thesis is limited to the conditions that prevail in Sweden.

1.4 Thesis guide

1.4.1 Definitions

Technical platform: Predefined technical solutions that can be used in the

design and configuration of a building. Can be specified in drawings, instructions manuals or implemented in CAD tools as executable code. A technical solution can be used together with other solutions ore by itself. The term product platform is sometimes used as synonym for technical platform

Process platform: Predefined methods, instructions and rules to be used

in the design, production and assembly process of a

construction project.

Building system: The combination of a technical and process platform,

i.e. contains both methods and technical solutions on how to customize, produce and assembly a building

following the rules set-up for the building system.

Modularisation: Decomposition of a product into building blocks

(modules) with specified interfaces, driven by company

specific reasons. (Erixon 1998)

Configuration: To put together a product from well-defined building

blocks (modules) according to a set of predefined rules

and constraints. (Hvam et al. 2008)

Configuration system: IT-system which can support the task of working out

specifications for customer-specific products. (Hvam et

al. 2008)

1.4.2 Outline

Chapter 1 Introduction;

This chapter introduce the research field to the reader and define the problem, purpose and aim of the thesis. Also, research questions are stated that have guided the researcher in the research work.

Chapter 2 Method;

In this chapter the researcher's context is described followed by a description of the research design and the research process. The method that has been used collecting data and the work executed in each paper is thoroughly discussed. The chapter ends with a short discussion of the validity and reliability of the results.

Chapter 3 Theory;

The theoretical framework consists of Modularisation, Configuration, and ICT-tools. These theories are well known in manufacturing industries but are in this chapter evaluated in the context of the construction industries way of working.

Chapter 4 Appended papers;

The appended papers are summarised in this chapter and result of the papers is also clarified.

Chapter 5 Discussion and Conclusions;

The final chapter discusses the findings of the research questions from the researchers background of a consultant. The chapter ends with concluding remarks and suggestions for further research.

1.5 Other publications

Except the appended papers presented in chapter 4, the researcher have participated in industry publications mainly presenting the practical implications of findings in paper 3 and 4.

Hamon, E., Jensen, P., (2008) Effektivt trähus skall trotsa höjderna, Teknik och Forskning, kundtidning från SP, nr 3

Jensen, P., Hamon, E., (2008) Utveckling av ett byggsystem för industriellt träbyggande, Väg och vattenbyggaren, nr 5

Lundgren, N. M., (2008) Nytt byggsystem för flerbostadshus i trä, Byggindustrin, nr 32,

Hamon, E., Jensen, P., Lessing, J., (2009) Utvecklar ett byggsystem för flerbostadshus i trä, Husbyggaren 10, nr 3

Also the researcher is the co-author of one conference paper, presenting the possibilities of configuration of building system using architectural objects;

Wikberg, F., Ekholm, A., Jensen, P., (2009) Configuration with architectural objects in industrialised house-building, presented at CIB W78, Istanbul

2 METHODOLOGY

2.1 Researcher's context and background

"Science is derived from the facts" (Chalmers 1999) and research results should be reproducible with the same outcome. However, science based on researchers' interpretation of the reality of a studied object does not necessarily produce the same outcome even though the object studied has been observed under the same circumstances. (Chalmers 1999) In this sense qualitative research results are highly dependent on the researcher doing the observation and do not necessarily need to be reproducible. This research is based on qualitative methods wherefore the researcher's background is of interest.

The researcher graduated as M.Sc. in Mechanical Engineering at the Royal Institute of Technology (KTH), Stockholm, 2005. The researcher has a major in structural design of wood structures and wood refinements processes at saw mills. The specialisation evolved in his master thesis, where the focus was to design and test a new kind of wooden beam using waste from the sawmill. After graduation the researcher was employed by Tyréns AB, an AEC consulting company, working in traditional construction projects as an engineering consultant. The first two years after graduation the researcher was primarily focused on ordinary consultant work, working as a structural design engineer, designing mostly residential buildings made from steel, concrete and wood. These job experiences have been most relevant as a starting point for the research work. It also gave an understanding of the difference between the construction industry and manufacturing industry's way of working. After two years the researcher joined the competence centre of Lean Wood Engineering (LWE). It is a joint-venture research centre between three Swedish universities (Luleå University of Technology, The Institute of Technology at Linköping University and Lund Institute of Technology) and twelve industrial partners, where Tyréns is one of them. Since 2007 the researcher has been working part time as a structural design engineer and part time as a PhD-student.

By combining research and work as a structural designer, the researcher has been able to identify and study real-life industrial problems and methods of working. The researcher has throughout his studies been able to apply results, methods and proposed solutions in the cases defined in chapter 2.3. This lead to a deeper understanding of the object studied, but at the same time questionable due to the closeness to the studied object. A direct contact with the studied object may create a deeper understanding of underlying problems, but can also be a threat to the validity of the results (Avison et al. 1999).

According to Widerberg (2002) it is essential to emphasize the influence of previous experiences when studying a business you know well and take advantage of your knowledge when defining the research objectives. A researcher must be able to shift from the closeness that the consultancy work gives to the objective distance required by the research work. Since most of the research been directed toward finding and evaluating new ways and methods not used in the researcher's company practice today, the risk for biased interpretation of observations of existing methods familiar to the researcher is diminished. Also, the empirical part of the research has been facilitated by the researcher's location at the head office for Tyréns in Stockholm. Scientifically, the research studies have been conducted at Luleå University of Technology, some 900 km from Stockholm.

2.2 Research design

According to Ackoff (1999) there are six phases in applied deductive research:

- 1. Formulating the problem
- 2. Constructing the model
- 3. Testing the model
- 4. Deriving a solution from the model
- 5. Testing and controlling the solution
- 6. Implementing the solution

These phases are not discrete stages done sequentially, they are in general performed in an iterative manner. The adopted research design has many similarities with Ackoff's (1999) theories; formulating the problem, gathering information from literature and interviews, construction and adoption of a

feasible model. Testing, controlling the model in an iterative manner until the solution been implemented in demonstrator software.

The methods used in this research are case study research with data collection from interviews, company archives and action-based research in the implementation and testing phase of the proposed solution. The difference is that in case studies, the researcher observes and interprets what the studied objects do. In action research, the emphasis is more on what practitioners actually do. (Avison et al.1999)

2.2.1 Case study companies

Company 1: Were established 2007 and is working with design and constructing of family residential houses. Their approach to the market is to deliver architectural designed houses in what they call collections of 3-5 new types of houses every second year. They deliver complete material and components needed above the foundation including assembling instructions. The company consists of 10 people working primarily with sale and development of new products. The responsibility of assembly of the house is left to the customer.

Company 2: Is one of Sweden's leading modular family house manufacturers. Since the start over 50 years ago, approximately 43 000 houses have been built. The company delivers turnkey houses and takes total responsibility for the delivery. Sales, design, manufacturing and on-site assembly are performed by in-house staff. The company exports houses to Denmark, Germany and Japan. Customers include both private end user and business to business clients. In 2008, the turnover was € 91 Million and in total the company employs a workforce of approximately 320 people. Houses are manufactured in both contemporary and classic designs and the targeted end customer group is predominantly middle- and upper middle class.

2.2.2 Case study

The case study approach focus on the process rather than the outcome. Yin (2003), defines a case study as "an empirical inquiry that investigates a contemporary occurrence within a real life context". In research question 1 and 2 the focus is on "how", which indicates that case studies are suitable. This method has shown to be useful for the researcher in understanding the underlying structure that forms the case evaluated. Also, it gives the researcher

valuable information of the area studied (Yin 2003). The study of the companies described in chapter 2.2.1 together with literature studies form the platform on which the model of implementation of the proposed solution is founded. When the solution is based on case studies the findings may be difficult to generalize, especially if only a few companies are studied. The proposed solution can only be valid for the case evaluated (Yin 2003). Therefore, the case studies has been complemented with literature surveys on similar proposed solutions, albeit most of which been implemented in the manufacturing industry.

2.2.3 Action Research

Action research generally involves active participation by the researcher with the purpose to influence the outcome and in some cases change it, (Robson 2002). Avison et al.(1999) argues that action research encourages researchers to experiment through intervention, later reflecting on the effects the inventions and proposed theories have resulted in. The principle of the action research method is to try out a theory with practitioners in real situations and gain feedback from this experience. Afterwards modifying the theory as a result of the gained feedback, and try it again. In the implementation of the theory of product models and technical systems in research question 3, the researcher was involved in the development process of the building system, the methods and research questions were therefore easy to implement in the process. The research outcome is highly dependent of the person involved in the action research. The subjectivity or perceptions are important factors to take into account. When the researcher has a main role in a project the validity of the outcome needs to be verified, an evaluation of the researcher and the participants are also necessary (Robson 2002).

Avison et al.(1999) define four types of action research fields;

- 1. Action research focusing on change and reflection
- 2. Action science trying to resolve conflicts between espoused and applied theories
- 3. Participatory action research emphasizing participant collaboration
- 4. Action learning for programmed instruction and experiential learning.

Here, item 1, 3 and 4 been used by the researcher in the research process of answering research question 3 and to some extent also research question 4.

2.3 Research process

The principle method has been to find a solution on a practical problem that can be generalized, but also to investigate how the solution changes the role of a structural engineer. The approach or the research process is governed by the research questions and the methods used and are what separates the researcher from normal engineer work. If the researchers cannot explicitly describe the process and research methods used, the work might be better described as consulting (Avison et al.1999).

The *first part* of the research, answering research questions 1 and 2, investigated the possibilities and problems with the introduction of building systems. The aim was to gain knowledge of industrialized housing processes and how building systems can be structured in sales, design and production. The two case studies were performed in parallel and the information gathered in each study was evaluated in the two separated studies, see figure 2.

The *second part*, answering research questions 3 and 4, was aimed to find solutions to implement configuration of building systems in the ordinary construction process. Findings from the first part of the research were used as a base to implement the proposed solutions in papers 3 and 4. The work was illustrated in demonstration tool that could be presented for prospective users. The tool and the "new work methods" was later evaluated in a series of semi-structured interviews with the help of students writing there master thesis. The investigation consisted of the developed building system and the constraints imposed on the design described in paper 3. Architects were interviewed to investigate how they would like to work with the design of the building system considering the imposed constraints. During 2-3 hours six experienced architects with different background were interviewed. (Sundström 2010)

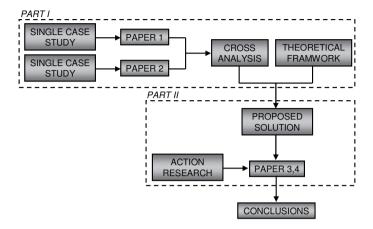


Figure 2: Research process.

2.3.1 Paper 1, Single case study

Paper 1 investigates how building systems based on modularisation principles can be developed. It also investigates differences between product and project orientated views. Information is collected from interviews with personnel working for company 1 described in chapter 2.2.1, to gain knowledge of the product from sale perspective and requirements and constraint of the technical platform from a production point of view. Semi-structured interviews were used to adjust and follow-up prepared questions during the interview, but also later on when new questions arose, (Wallén 1996). Also archival analysis of drawings, assembly instructions, and sales material were performed. The literature studies performed during the first case study were primarily based on the theory of modularisation with the intention to define a hypothetical to-be process based on modularisation. After the case study some of the results were implemented in the case study company. The researcher had a central role as the structural design engineer with the intention to develop the building system that was going to be used in the future. The use of new ICT systems and the integration between the design team and the factory personnel made the project unique in comparison with other construction projects. The first case study also laid the foundation for the development project described in paper 3.

2.3.2 Paper 2, Single case study

The second case study conducted on company 2, described in 2.2.1, was performed with the purpose of investigating how a building system can be adapted to customers' requirements. First, the sales office was interviewed, see appendix A were the questionnaire is appended, and thereafter the production and engineering staff to understand how the constraints of the building system were dealt with. As in the first case study, archival analyses were conducted of the material that defined the building system such as drawings, assembly instructions, productions instructions and sales material. methodology was used in interviews with employees as in the first case study. A first description of the product design and production constraints was established and illustrated in product views. These views were used to refine and verify the product structure of the building system with the engineering department in a workshop. The refined version presented after the workshop is the version published in paper 2. After the company verified that the product structure was correctly understood, a cross analysis was performed of what customers want when buying houses and what the company could offer. The analysis was made to compare customers' desires and demands with the company product offer. The customers demand was based on a Swedish Internet survey performed 2008 (Horsman 2008). The survey received some 5000 answers from people in ages between 18 to 65 years. The result of the survey was also confirmed with the sales office in Stockholm. The theoretical framework in this case study was based on Modularisation, Configuration and Product modelling.

2.3.3 Paper 3, Action Research

The wood institute in southern Sweden announced a design competition on the development of a multi-story timber building, 4-8 storeys high. Tyréns AB, entered the design competition with a multi-skilled product development team, consisting of architects, structural design engineers, clients (future proprietors), construction site managers, site managers in factory, and process engineers. During one and a half years the team worked together in order to develop a building system. The process engineers were in charge of the development project and responsible for updating and managing the technical and process platform developed in the project. The researcher worked as a structural design engineer and had a leading roll in the design of the building system according to modularisation principles and development of configuration tools. This method of research by participating in real-life situations can be described as consulting, and the researcher needs to explicit follow the tenets of action

research (Avison et al.1999). To evaluate the result from the action research on the development of the building system, an "evaluation sheets" were introduced. This enabled the researcher to document the development process and the development of the building; it also gave the development team a strait forward approach with clear check points. Paper 3 illustrates the proposed "to be process" based on modularisation and configuration.

The building system is going to be implemented and further research will be conducted on the application of the building system in the first real project.

2.3.4 Paper 4, Implementation

In paper 4 prototypes of the developed configuration tools from the development project are presented. The paper illustrates how configuration of a wood floor slab module can be integrated in engineering and architectural design tools containing the constraints from production and assembly of the product. This paper is an example of how the proposed solution defined in paper 3, can be implemented in existing ICT-tools. Some preliminary results of the use by architects' are also presented.

2.4 Validity, Reliability

According to Yin (2003) there are four different tests for to ensure validity and reliability when conducting case study research;

Construct validity- includes assuring that gathered information is correct, when using multiple sources this can be accomplished through triangulation. Having key informants study the report before it is final is another commonly used method. This was done in paper 2 where the key personnel were involved in a workshop verifying that the information gathered was understood correctly. Also, the result of the survey was confirmed by sales staff.

Internal validity- refers to finding causal relationships, for example the case study conducted in paper 2. When trying to find the answer to why the company failed to deliver and build according to the building system? Is it because the salesmen did not know the constraints of the building systems or was it because the system was not designed to offer customer attractive products? Or is there any other relationship that is not yet known? The processes and changes in a development project are also difficult to duplicate. The validity in this case relies on the experience and knowledge of the development team. The team consisted of many disciplines with deep

knowledge and triangulation of data from different aspects could be accomplished. Yin (2003) argues that this test may have difficulties when inferences can be hard to verify. It is important to be able to ensure that all explanations and possibilities have been evaluated and considered. But internal validity also implies the "Inner logic", verifying that words spoken are correct and linked. This has primarily been satisfied in the review procedures of the appended papers (Yin, 2003).

External validity- Deals with the problem of knowing if the study performed can be generalized. According to Yin (2003) this is a major problem when conducting case studies. However, the researcher can analytically generalize the results from one set of investigation to a broader theory. Referring to this definition the proposed solution in paper 3 has in a sense been generalized from the conclusions made in paper 1 and 2, with literature studies. Yin (2003) argues that a theory must be tested in at least one or two tests to support strong evidence for the generalization, in this sense the proposed solution may be questionable, but still the research has not completed the research loop defined in the applied research model according to Ackoffs (1999). The proposed solution is only in the testing phase in the research loop.

Reliability- "Science is derived from the facts", (Chalmers 1999) and should be reproducible. The result from research performed in paper 1 and 2 can be verified from literature were similar studies have reached resembling conclusions. When it comes to the proposed solution and the action research performed in the studies presented in paper 3 and 4 the reliability is consider to be low. The researcher has in many ways affected the result therefore making it difficult to reproduce. Adjustments and changes in the development project are difficult to duplicate. Since the researcher has been working close to the industry the usefulness of the result can in a sense be confirmed. However, the result of the action research in paper 3 and 4 shows only one possible solution out of many. The solution can only be judged to be better or worse in comparison with other solutions.

3 THEORETICAL FRAMEWORK

3.1 Configuration processes

Mass customization has evolved from the keen competition between companies of adapting mass produced products to customer needs without compromising delivery time, price or quality, (Pine 1993). Mass customization combines the customization process often used in hand-craft manufacturing with mass production technology, (Gerth 2008). In the shift to mass customization, development of product platforms from which customized products can be configured in a configuration process has evolved (Simpson 2003). Figure 3 shows a typical configuration process often used in the manufacturing industry.

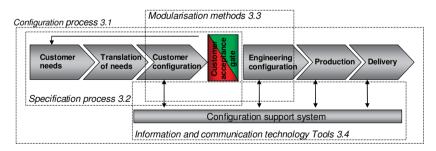


Figure 3: Configuration process and theoretical framework that is treated in this thesis. Adapted from (Gerth 2008; Hvam et al. 2008).

The process begins with finding and translating customer needs to preliminary specification and functional requirements used in the customization process.

This specification process often involves the use of question design templates and control of the preliminary design according to quality, manufacturability, delivery time, costs, etc. The preliminary design is presented to and accepted by the customer; else new input from customer needs to be re-evaluated. This specification process will be described in more detail in section 3.2. When the customized product is accepted by the customer, engineering configuration can begin. The customized product is thereafter produced and delivered, (Gerth 2008). Compared to construction where the final assembly of the product is made at the site, the product is finished when it leaves the assembly line in the manufacturing industry, (Winch 2003).

Product configuration is an effective way of structuring products composed of standardized parts but also as a method of presenting products to customers, bringing better control over the product range (Hvam et al. 2008; Jørgensen 2005). The concept of a configuration system is also known as constrain-based programming, where the solution space is defined and can be illustrated by a set of rules determining how components and modules can be combined into products. Additionally, products structured in a product platform become the company common view of the product range that can be shared by sales, design and production departments. In the work with product customization many industries have developed methods to design product platforms (Mark and Ishii 2002; Marion et al. 2006; Deepak et al. 2006; Veenestra et al. 2006). These platforms can be configured either by adding, removing, or substituting modules to the platform or by scaling the platform in one or many direction to target a special market, (Simpson 2003). According to Hvam et al. (2008) product customization consists of two central principles; "product ranges should be developed on the basis of modules, and configuration systems should be used to support the task involved in the customization of the specific products, making it able to address different stakeholders and disciplines within the product range". Product modularity is the framework which both the specification process and the detailed engineering and production configuration process are depended upon. The reuse of existing modules in the development of new customized products is a competitive advantage of modularized product platforms, (Anderson and Pine 1997). Product modularization will be described in more detail in 3.3.

The key to a successful use of the configuration begins in the specification process of the product variety and definitions of the product platform. In this work, UML (unified modelling language) or EXPRESS has often been used as meta-model, defining the product structure (Hvam et al. 2008; Wikforss 2003; Eastman et al. 2008; Jose and Tollenaere 2005). Hvam et al. (2008) describes a

way of sorting the product variant master into separate views; Customer, Engineering and Production view. By doing so different stakeholders rules and constrains can be entangled describing the product range. The work with identifying the structures begins with UML-notation and generalizing the structure.

3.2 Specification processes

The specification process can be handled differently by companies. It is a strategic decision where the decoupling point is placed, figure 4. The specification process in this thesis does not incorporate the collection of customer needs, the translation of customer needs to design data or the actual conceptual design.

Duray (2002) defines a configuration process as a concept using modules that can be combined according to customer needs. According to Duray (2002) companies can be categorized into four categories; Fabricators, Involvers, Modularizes, and Assemblers, depending on where the customers' enters the product specification process. The location of the customer order decoupling point will affect the modularisation and according to Duray et al. (2000) products that have many configuration options are often using "cut-to-fit modularity, see figure 5. Similar ways of structuring companies according to customer orders decoupling point are illustrated in figure 4, (Hansen 2003, Winch 2003). The "Engineer to order" companies often supply complex customized products where the product specification process starts based only on norms and standards. The traditional construction project can often be characterized as engineer to order or in the case of design-bid-built projects as concept to order, (Winch 2003), where the architect starts the product specification process with the conceptual design. The "Modify to order" companies produce customized product based on technical platforms. These kind of construction platforms have recently been introduced on the market by the major construction companies in Sweden, e.g. Skanskas Xchange, NCCs Bostadsplattform, PEABs PGS system, (Andersson et al. 2010). The "Configure to order" company products are based on modules and standard parts that can to great extend be configured to satisfy customer needs. These types of complete products are less common in the construction industry. The NCC Komplett, was highly configurable building system launched in 2006 but closed down when the target "half the price and twice as fast" was not reached fast enough. Also a new configurable building system has recently been introduced in Sweden - the "Bau-how", (Andersson et al. 2010). The last category; "Select variant", are companies working with product portfolios from where customer can select a certain product that can be altered to some extent. Many of the producers of family houses in Sweden can be classified in this category. Skanska ModernaHus is an example of a select a variant type of a multi-storey building system from which the customer can select among 6 house types from 3 to 8 storeys. These house types can then be altered with additional choices, such as exterior design, energy efficiency etc.

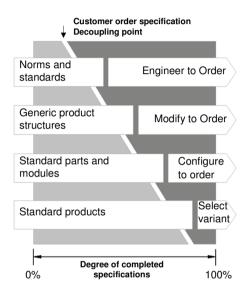


Figure 4: Customers entry point in the product specification process.

3.3 Modularisation methods

Modularisation is a method used in various industries with the aim of satisfying different customer needs while keeping standardised production (Baldwin and Clark 2000). Ericsson and Erixon (1999) defined modularity as "increasing efficiency by reducing complexity", the increasing demand for custom made products made the number of product variants to explode since the 80's. Modularisation provides the possibility of offering a variety of end products with fewer components. The assortment into modules makes it possible to use parallel production of the product, shortening lead time, quality improvements and shorter feed back loops (Erixon 1998). According to Jørgensen (2001), the main advantages are that the end product can vary in shape and functions, but the design and production of components and modules within a product family

are the same. Two factors are of great importance when developing a modularized system; independence of components and interfaces (Erixon 1998; Vorrdijk 2006; Hvam et al. 2008). Baldwin and Clark (2000) argue that when a system is divided into smaller parts or modules, the complexity of the system can be concealed behind "an abstraction and an interface".

Modules as a term are clearly separated in the manufacturing industry and construction industry. Modules in construction industry are often referred to as "standard building elements or volumetric pre-assemblies" (Höök 2005). Bertelsen (2005) defines subsystems, such as bathroom, kitchen, facades, etc. used in construction as modules. And the shortened lead time modularisation gives in the construction industry is the preproduction of components off-site. In other industries Ericsson and Erixon (1999) states that subassemblies are often the result of assembly planning activity but modules are chosen for a specific strategic reason for the company.

Three types of modularization can be defined; Product modularity, Process modularity, and Supply chain modularity (Lennartsson 2009). This research is primarily concentrated on product modularity and will be described next.

3.3.1 Product modularisation

Product modularisation is the arrangement of products into building blocks with specific functions and interfaces; see definition in chapter 1.4.1. According to Ericsson and Erixon, (1999) the product structure is the key to non-complex product platform and can be treated on three levels; Product range level, product level, and component level. The relationships between these levels will affect the complexity of the product exponentially and decisions made at the product range level are therefore crucial. In the assortment of a product platform into modules Erixon (1998) have defined the concept of "Module Drivers", which covers the products entire life cycle and the reasons for their development. To support product developers Erixon (1998) developed a method called MFD (Modular Function Deployment) that systematically investigates different modularisation strategies of a product.

The MFD method consist of 5 steps and starts with the definition of customer needs in a specific market segment. With the use of a simplified QFD (Quality Function Deployment) the most important customer requirements are identified. QFD is a method for introducing customers values and needs early in the design process. The values are then prioritized and mapped against the product properties, (Akao 1990). These kind of system analyses are well

known in the manufacturing industry and performed by market analyst. Architects can be said to play the same role in the construction industry, guiding the client in the development of the building program, (Bertelsen 2005). The first step in MFD is to identify what is important and generates value for the customer. One approach is to standardize parts and modules which are invisible or indifferent for the customer. The visible parts and modules should be open for product customization, (Bertelsen 2005). Erixon (1998) have named these module drivers "Different Specification" and "Styling". Step 2 in MFD is the selection of technical solutions that later on are analysed regarding their reason for arrangement of them into modules, (Step 3 in MFD). After the modularised concept is generated it is evaluated and improved, using DFMA (Design for Manufacturing and Assembly). Another methods that have been proposed when arranging products into modularised platforms is the Design Structure Matrix (DSM) (Baldwin and Clark, 2000). DSM can be used to map hierarchal relationships and independence of design parameters. These arrangements of the product can later be described in four different task structures; Independent block, Strict sequential, Hierarchal block, and Hybrid, when evaluating how the product will be modularised.

In the work with modular products, Ulrich (1995) defines three types of modular systems; Slot modularity, Bus modularity, and Sectional modularity, illustrated in figure 5.

Slot modularity: is when modules can be connected in a certain position using a standardised interface. There are four types of slot modularity; Component-Sharing, Component swapping, Cut-to-fit and Mix modularity.

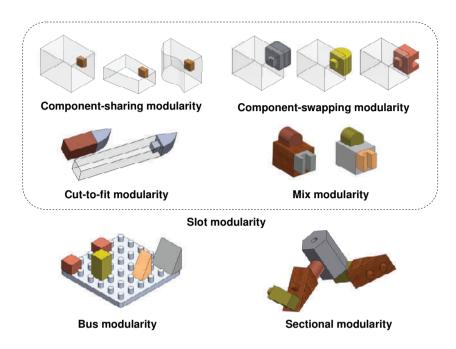


Figure 5: Different types of modularity adapted from (Ulrich, 1995).

Component-sharing modularity: when two or more modules contain one or more of the same basic components as the core upon which they are built. For example an elevator that can change geometry of the basket but uses the same hoisting apparatus.

Component-swapping modularity: is when two or more alternative types of components are paired with the same basic product body to create different product variants.

Cut-to-fit modularity: has the property of parameterization, where the interface of the module is the same but the dimensions can change. Cut-to-fit modularity has been used in many applications in the construction industry, such as walls and slabs etc.

Mix modularity: combines several standard components together to create a new device. Example could be the colour of a house.

Bus modularity; is the ability to add extra modules to an existing series of product, can be illustrated in construction industry as the foundation where different kinds of wall modules can be placed on and where the interface is defined.

Sectional modularity; is when modules has standardized interfaces where the modules can be combined in several manners and is used in the construction industry in the assembly of prefabricated components such as windows and HVAC systems.

3.4 Information and Communication Technology tools

3.4.1 CAD in the construction industry

There are two different methods used in CAD, entity oriented and object oriented modelling. When CAD was introduced, the construction industry did not recognize the benefits of CAD tools based on object oriented modelling. Instead entity-based modelling of graphics elements was introduced in the construction industry in architectural drawing tools such as AutoCADTM mimic the traditional way of working with paper based drawings. The CAD tools used in the construction today uses object oriented modelling such as; RevitTM, ArchiCADTM, etc. that are derived from the object oriented parametric tools used in the mechanical industry. These CAD tools are commonly known as Building Information Modelling (BIM) software. (Eastman et al. 2008) According to Sacks et al. (2003) 3-D modelling software must support a topdown design process with three distinct phases: assembly layout, assembly detail, and piece detailing, whereas conventional construction object-based applications primarily focus lies on assembly layout with predefined "base building objects" (Eastman et al. 2008). In the work with integrated modelbased design, Kunz and Fischer (2009) define three levels of virtual design and construction (VDC). First level "Visual 3D and 4D models", second level "Building Information Models" and the third level named "Knowledge-based models that support automation" that uses parametric models to automate routine work, such as piece detailing.

3.4.2 Parameterisation

The idea of parametric modelling is that shape instances and other properties can be defined and controlled according to a hierarchy of parameters at the assembly and sub-assembly levels, as well as at an individual object level, (Eastman et al., 2008). When CAD application tools such as RevitTM are

developed to assist the conventional construction process, these parametric support systems are developed to certify that all kind of technical solutions can be incorporated; "base building objects" (Eastman et al. 2008). When working with "Knowledge-based models that support automation" (Kunz and Fischer 2009), constraints of the system needs to be implemented in the design tool. Gross (1996) uses a constrained based design program called CKB, using grids in different levels and component object design rules. Similarly to Lessing's (2006) "industrialized house building process" with separated processes for development and project configuration, Gross (1996) support two phases in the design process; the design of the configuration system and the configuration of the project. According to Gross the CKB program is not intended to force architects the use of a single predefined technical system. Rather, CKB provides the ability to define technical systems. Nassare et al. (2003) illustrates a constrained based cad application named EASYBUILD, a prototype of an extension pack for AutoCADTM. The program uses different levels of detailing when supporting the architect in automating parts of a design. However, design automation using constraint based programming in CAD tools that is used in the conventional construction industry is difficult to implement since such programs needs to be programmed using the API (Application Programming Interface), and programming languages like LISP and C++.

Johnsson et al. (2006) advocates the use of specialized software to solve problems they are designed for. Manufacturing industry has been working with rule-based programs since 1984 (Sandberg 2007) and has developed "expert systems" known as KBE, built on logic expressions and Boolean operators, (Hvam et al. 2008). The developed KBE system focus on design automation using object-oriented programming, configuration and engineering knowledge, (Sandberg, 2007). Sandberg et al. (2008) are, for example, using a rule based parametric CAD application normally used in the manufacturing industry in design automation of the connection between the stair and a wooden slab. One CAD-application used in the construction industry, ArchiCADTM, can with the use of a description language, GDL (Geometry Description Language), support programming of objects with constraints and design rules in the architectural design. "NCC komplett" used this methodology to support the architectural designer before the design information was transferred downstream to engineering were a mechanical CAD tool was used to execute the piece detailing in production of sub assemblies in the factory, (Andersson et al. 2010).

3.4.3 Configuration systems

There are primarily two different types of configurators: sales configurators and engineering configurators. One type of engineering configurator is expert systems based on KBE (Knowledge based engineering), (Hvam et al. 2008; Nanua et al. 1997). Sale configurators are usually developed when the decoupling point is close to completed specification, i.e. ranging from select variant to configure to order. Engineering configurators are developed when products are highly configurable, configure to order - modify to order. When the solution space becomes larger traditional engineering methods are used.

Sale configurators have the purpose to guide customers in the specification process of the product illustrating constraints and possible solutions. Simpson (2003) argues that even though some companies are marketing a variety of products, this is not mass customization. The sales department needs products with modular architecture that can be tailored to satisfy customers needs (Jørgensen 2005). A customized product comes when satisfying a specific customer, and therefore this customer must be involved in the product specification process. Duray (2002) states that even if customers are involved in the definition of the product, but the production is not built on modularity this is not mass customization.

The implementation of the sale configurators can either be put in the hands of the customer or be presented by the sale personal. Gilmore and Pine (1999) argues that Web-based customization systems are opening new paradigm towards one to one marketing. Olofsson et al. (2004) shows how a web-based configuration system can be implemented in the selection process of an apartment. Apelberger et al. (2007) describes the Sekisui Heim configuration process when Sale staff are using the ICT-program "HAPPPS" with the configuration of customized homes.

Engineering configurators aims at speeding up engineering design by reusing earlier results and knowledge. With the use of expert systems it is possible to automate time consuming engineering activities, relocating time into improving old solutions ore finding new ones (Hvam et al. 2008). Another motive of engineering configurators is to establish a link between the sales and the production. The most often used knowledge representations in expert systems are: structured objects, logic and If-Then rules. Structured objects refers to semantic networks and frames. Semantic networks is a collection of objects known as nodes that is connected to one another via series of relationships. Frams is a clarification of structured objects with associated

descriptions. The object-oriented technologie rely on boths the semantic networks and frames and thogether this forms the basis for what we call classes. Logic is the derivation that takes place when conclusions can be based on logical expressions evaluated true or false. Boolean operators are often used in the logical expressions and the statements is also denoted composite propositions. Knowledge can also be defined by a set of IF-Then rules (Hvam et al. 2008). Johnsson et al (2006) describes a demonstrator of an expertsystem based on rule-based design used early in the configuration process of a building block. Apelberger et al. (2007) describes the configuration system for "NCC-komplett" as the "brain" of the factory, that controlles the production equipment in the factory.

3.4.4 Information exchange

Design tools with well defined information structures and communication possibilities with databases and other ICT-applications have shown to be of crucial importance in the manufacturing industry. Tools used in the construction industry often lack this possibility, (Ekholm et al. 2008). Information exchange in conventional construction projects is often done using drawings and documents, distributed via document servers, FTP servers or email (Zhinling et al. 2004; Samuelsson 2003). Much of recent research has been focused on improving the information flow in the traditional building process focusing on interfaces between discipline specific analysis and design software (Kunz and Fischer 2009; Eastman et al. 2008). In this work the definition of common data format, IFC (Industry Foundation Classes) has evolved. However, the use of IFC when transferring information between different ICT-tools is still problematic with information losses and distortions as a result of poor implementations, (Pazlar and Turk 2008; Ekholm et al. 2000). The vision of a shared building information model, where all information can be stored and used by separate stakeholders appear unrealistic, (Wikforss et al. 2003) Therefore, the information exchange between different type of applications rely on propriety data format, application specific exchange protocols or add on solutions, (Racz and Olofsson 2009). Many of the application specific solutions is based on XML (eXtensible Markup Language) as the transport mechanism for exchange (Zhinling et al. 2004; Norberg 2008).

3.5 Conclusion

In Lessing's (2006) "industrialized house building process", see figure 1, the solution to increase the productivity in the construction industry is by restructuring the building process into a product and project development process. The customer entry in figure 4, defines this decoupling point between product and project development process, hence the kind of technical platform that the company select to develop will also affect the position of the decoupling point, the specification process and also what kind of ICT tools needed supporting the task of configuration the project. The three levels of implementation of VDC as described by Kunz and Fischer (2009) seems to be closely connected to these customer order decoupling points. The Engineer to order primarily uses the first visual level of ICT integration. The second level referred to as the Building Information Models is suitable in the *Modify to* order specification process based on technical platforms. The Configure to order needs "Knowledge-based models that support automation". This level seems to be closely connected to building systems and constrained based programming using parameterization, (Sandberg et al. 2008).

New tools and implementation of configuration processes affect methods used but also process, organisational structure and culture, Woksepp (2007). The theoretical framework in this thesis covers mainly tools and methods in a specific process; the configuration of modularised products. The role and organisational structure of a specific company is highly dependent of the customer order decoupling point. For example an AEC-consultant company can't work in the project specification of a Select variant kind of operation since those companies working close to completed specifications need to own the whole process. Gerth (2008) states that configuration strategy is directly related to how the generic product model and how production system is built, but also how the configuration of the customised product is performed. If AEC consultant companies want to develop building systems for construction companies in the Select variant or Configure to order type of business long term alliance-based relationship between the AEC consultant and the construction company is needed, (Eastman et al. 2008). Also, these kind of building system can only operate in a design build environment.

4 APPENDED PAPERS

4.1 Paper 1, Reducing complexity of customized prefabricated buildings through modularisation and IT-support

Objective:

Paper 1 addresses RQ 1, how modularisation principles can be implemented in the construction industry, with the aim to explore methodologies for customization used in the manufacturing industry.

Summary:

Companies using prefabricating strategies are often adapting the building system to customer requirements using ad-hoc solutions that do not fit their production system. The paper presents the result of the first part of a case study in which a modularized building system is developed with the intention to be adaptable to customers requirements and still fulfill the constraints imposed by the production system. The proposed configuration process consists of components and modules that can be configured into a customized building, see figure 6. The development process implemented in the case study consisted of a workshop using QFD (Quality function deployment), and interviews with key personal from the case study company and the production company responsible for production of components, modules and assembly of the product. The intention was to define customers' requirements for the selected market "niche" for the company as well the constraints imposed by preproduction, transport and assembly on-site.

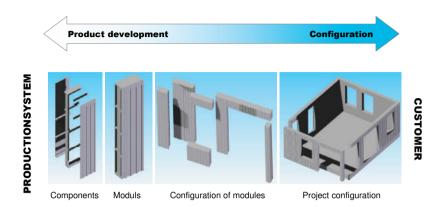


Figure 6: Configuration of the proposed modularised building system in paper 1, and affecting needs in the development phase.

Result and contribution:

The result of the work conducted in paper 1 was later implemented in the case study company in Solid WorksTM where the components of the configured modules could be exported to ExcelTM for cost estimation purposes. The walls were separated into start and end modules, wall modules, and different window modules, see figure 7. Each module was modelled with all the components, such as insulation, beams, etc. The modules were assembled into walls before they were transported and installed on-site. The introduction of modularisation methods in construction require complete and stable design requirements over the life time of the product offer and therefore it is essential that the product owner has control over the whole process when working with "select variant" defined in figure 4 chapter 3.2.

In this paper I was the main author, Thomas Olofsson assisted and reviewed the work. Marcus Sandberg and Linus Malmgren commented on the content of the paper but weren't part of the actual work performed in the study.

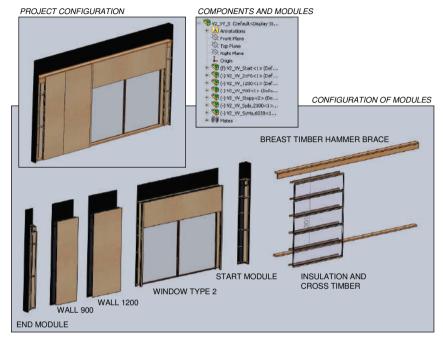


Figure 7: Breakdown of product structure into building parts that can enhance flexibility in further product development.

4.2 Paper 2, Product modeling of configurable building systems

Objective:

Paper 2 addresses RQ 2, *How can information of customer requirements and building systems be managed*, in a case study of an existing building systems. Especially the flow of information from sales to realization of the building was investigated and how the flow can be managed by the use of product modelling technology.

Summary:

The work was based on both archival analysis of the building systems constraints and interviews with engineering, production and sale departments. To be able to define customer needs a Swedish customer survey which ranks

features that customers prioritize when buying detached houses are compared with what the company's product platform offers.

Result and contribution:

The work performed in this paper resulted in a product description of the case company's product model. This was illustrated in four different views, customer, engineering, production, and assembly view. The different views are adapted for the different stakeholders in the building process and illustrated in figure 8. It is concluded that product modeling is a suitable technology to describe the product structure of modular houses. It also gives the manufacturers the opportunity to get a common understanding of the company's product range. Creating adapted views makes the product structure less complex to use in the configuration and production process. The case study also showed that product development of modular houses must start from customers' requirements. Otherwise the risk increases for ad-hoc customization solutions propagating to manufacturing and assembly on-site with considerable higher cost as a result.

In the work with this paper my former college Linus Malmgren and I were conducted the case study together. Linus Malmgren focused on product modelling technology and I on how the company addressed customer requirements in the sales, engineering and production. The work presented was written together and all solutions and conclusions evolved in this process. Thomas Olofsson assisted and reviewed the work.

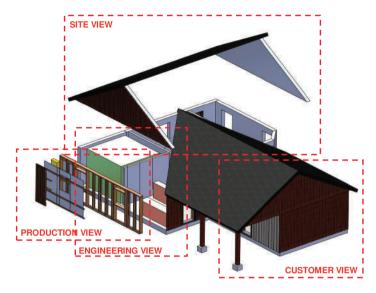


Figure 8: Illustration of different views of the same product.

4.3 Paper 3, Product development through LEAN design and modularisation principles

Objective:

Paper 3 describes the development of a modularised building system that can be customized using configuration methods. It addresses RQ 3, *How can configuration be realized in a modularised building system*, but also how lean principals and methods can be used in the organisation of the development process.

Summary:

The wood institute in southern Sweden announced a design competition for a multi-storey timber building system. The researcher was part of a multi-skilled team responsible for the development of a configurable building system. The researcher worked as a structural design engineer in the project and introduced the concepts of modularisation and configuration. The upper part of Figure 9 was used as inspiration and an example of a well known configurable product

and defines the fundamental principles of modularisation and configuration process. The methods of Quality Function Deployment, (QFD), described in paper 1 and mapping of customer's requirement, described in paper 2 and in "Configuration with architectural objects in industrialised house-building" (Wikberg et al. 2009), were used in the development of the building system. The developed building system will be used in the design and production of a new multi storey timber house located in Malmö, Sweden.

Result and contribution:

The paper shows how a multi-skilled team can consider the architectural design of the building system which integrates the manufacturability and assembly process of prefabricated modules on the construction site. A modularized approach in the design and construction of multi-dwelling properties offers a solution in design of customized buildings. The lower part of figure 9, illustrates the developed building system, and the arrangement of "Components and Modules" - "Configuration of modules"- "Configuration of project" defined earlier in figure 6. The modularisation principles of components and module variants and the configuration process of customized buildings are similar to Scania's configuration of trucks. Components are structured into modules such as a floor module and a ceiling module. These are structured into a floor element that can be transported to site, where the final assembly of the configured building is done. Standardised technical and process solutions can be repeated and improved over several projects. Configuration tools can be developed to support information flow downstream and constraints imposed by the building system upstream. Communication with stakeholders can be supported by the different views of the building system, preventing "ad-hoc" solutions propagating downstream the value chain.

In the work with this paper my former college Emile Hamon were working as a process engineers and implemented LEAN design methods and was also the leader for the whole development project. I was in charge of the structural design engineers for the building system in the project. The work presented was written together and all solutions and conclusions evolved in this process. Thomas Olofsson assisted and reviewed the work.

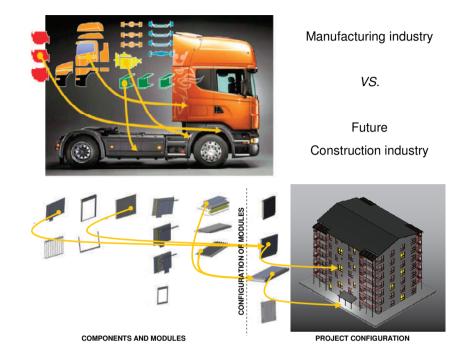


Figure 9: Configuration of Scania trucks (Gerth 2008) and project configuration using a modularised building system.

4.4 Paper 4, configuration through parameterization of building component

Objective:

Paper 4 addresses RQ 4, *How can existing ICT-tools support the configuration of a building system?*. This paper demonstrates the possibility of of parametric ICT tools in configuration of building system development.

Summary:

Based on the building system developed and presented in paper 3, an ICT-configuration demonstrator of the slab module was developed. The work started by structuring the necessary information that had to be managed and transferred upstream and downstream the value chain. This information was

programmed in the engineering view with the use of the CAD application Solid worksTM and the configurator Tacton works studioTM. In the engineering view information can be generated and trensferred downstream to the production view, such as production drawings, assembly instructions, article numbers of components and also CNC-operation codes making it possible to use automated machinery. In the customer view the building system constraints, such as width and length parameters are implemented in a CAD-application tool often used by architects, in this case Revit StructureTM. The building system module is loaded into the CAD-application and can be used just as for example window objects.. The configured module objects are exported downstream trough a filter using XML-format. Figure 10 shows the information transfer upstream and downstream the value chain.

Result and contribution:

The file created in the customer view is a functional model of the building constructed from predefined modules of the building system. By just defining the geometry of the different modules in the CAD-application used by the architect, the size of the file can be kept small. The more detailed information needed to manufacture the module is generated and stored in the engineering view. This way of handling design information makes it possible to handle large complex structures with ordinary computers. By separating the different views and using ICT-tools familiar to the architectural discipline, drawings can be generated that the building industry is used to handle. The architectural model is used to make drawings for the building permit and the assembly of the prefabricated modules later in the assembly view. Solid worksTM, used in the engineering view is more suitable to use when it comes to the development of CAD application for the parameterisation of prefabricated modules that are easy to maintain. The demonstrator clearly shows that when minimizing the number of parameters that can be altered in different modules, the information exchange between different programs can to a great extent be kept small.

The engineering part of the demonstrator with describing rules and implement it into the CAD-application was done by me. The work with designing the family of slabs in RevitTM my college Joel Liedbergiushelp me with the design. Thomas Olofsson and Helena Johnsson assisted and reviewed the work.

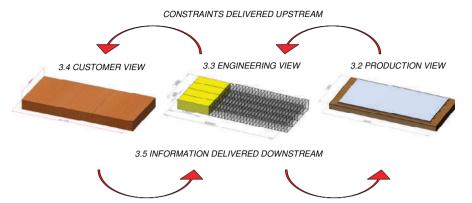


Figure 10: Integration of information between separate views in the slab demonstrator.

5 DISCUSSION AND CONCLUSION

5.1 Answering the research questions

5.1.1 Research question 1

How can modularisation principles be implemented in the design of building systems?

Based on the work performed in paper 1, the following condition must be met. The company owning the building system need to implement a product-oriented development process. Only then can modularisation methods used in manufacturing industries be implemented. The configuration process, as defined in figure 6, encompass essentially all needs and constraints that have to be considered in the design of the modular building system. The process is focusing on customer's needs but must respect the system constraints to be able to deliver the customized building at a competitive price. The work with modularisation methods starts with need finding since the design requirements from project to project need to fulfilled. However, there is no size fits all'; and it is therefore essential to target a specific segment of the market or product niche. Also it is essential that the selected customer order decoupling point between product and project development is respected by the company since this will affect the development of the modularised structure and the configuration system of the building system.

5.1.2 Research question 2

How can information of customer requirements and building systems be managed?

When comparing product offers to Customer top ten demands, (Horsman 2008), the case study performed in paper 2 shows that too little attention to customer needs makes the product harder to sell. To be able to satisfy the customer demands, the sales department unknowingly violated the constraints of the building system that led to ad-hoc solutions propagating to manufacturing and assembly on-site with considerable higher cost as a result. Similar results have been found in other studies (Andersson et al. 2010: Johnsson et al. 2006), and therefore a method for transferring information and constraints of the building system upstream and downstream the value chain is needed. If the product structure can be defined in separate stakeholder adapted views in the configuration process, the product range becomes easier to understand and less complex to manage. Rules and constraints of the building system can then be transferred upstream from the assembly, production, and engineering view to the customers' view and hence define the customisation limits of the product family. From these views the customer demands versus system constraints can to a greater extent be evaluated and used in the development of building system. I believe that an important aspect of customize-to-order configuration systems and their ability to satisfy customer needs without compromising the constraints of the building system lies in the integration and information exchange between the view specific ICT-tools.

5.1.3 Research question 3

How can configuration be realized in a modularised building system?

The research performed and presented in paper 3, shows how a multidisciplinary development team can be organised and supported by Lean methods and modularisation principles. The work with finding FR (functional requirements) and the structured meetings created a pull in the development process. Also the development of "evaluation sheets" that evaluated pros and cons of the technical solutions made the work continue as progressed. The view-specific organisation of FR made the building system easier to modularize. Also, having modularity in focus early established the right "mindset" in the development phase, i.e. according to Modular Function Deployment, step 1 (Ericsson and Erixon 1999). Modularization methods supported by CAD application tools appear to be the engine that can support the customisation process of a building system. If the system is built on modules the information delivery upstream and downstream the value chain can be simplified. Also the possibility of encapsulating the information and constraints in view-specific ICT-tools makes it possible to use mechanical CAD applications that easier manage output to Computer Numeric Control (CNC) machinery, version control, and change management support with the use of Product Data Management (PDM) and Product Lifecycle Management (PLM) systems.

5.1.4 Research question 4

How can existing ICT-tools support the configuration of a building system?

When products are structured into standard parts and modules, this opens the possibility of a configuration process. The breakdown into views addressing different stakeholders in the customisation of the product enables the use of ICT-tools that can satisfy demands in different parts of the design process. Rules and constraints can be concealed and information transfer kept small. In the architectural configuring, in the customer view, the tools normally used in the construction industry can be adapted, e.g. using developed module objects. When referring to systems that can handle the detailed design in the engineering view, parametric tools and product configuration systems used in mechanical industry are recommended. Selecting proper tools for the different views and minimise information transfer between them will be a prosperous way of working. The demonstrator illustrated in paper 4, shows one implemented solution of how information and constraints can be managed and transferred upstream and downstream using view specific ICT-tools. I believe that the use of these systems will also affect the disciplines way of working and probably introduce new roles, e.g. configuration controller.

5.2 Contribution

Scientific contribution:

- Aspects on of how to implement modularization methods in the construction industry.
- Possible ways to structure information and transfer constraints between different stakeholders.

Industrial benefits:

- The physical building system that is now to be implemented in the first project.
- What kind of ICT-tools seems to be feasible to use in the configuration of projects, and how the exchange can be implemented.

5.3 Concluding remarks

According to Lessing (2006) an industrialized building process consists of a development phase of the building systems and a project specific configuration phase. The work performed in this thesis covers both the development process and the configuration of building systems, with the aim of finding new ways to introduce this process in AEC consultancy companies. In the work performed from the conclusions made I have the following advices to AEC consultancy wanting to start to work with building systems:

- In the development process all disciplines working with the building system need to be included. Start with customers needs for the targeted market segment resolving them into important functional requirements always keeping the constraints of the production system in mind.
- The technical platform needs to be based on modularisation, with respect to the selected specification process, i.e. the customer order decoupling point and targeted market "niche".
- In the modularisation of building systems always have the configuration process in mind; developed modules and module variants need to be implemented in view specific ICT-tools.

When referring to the actual configuration of building systems:

- Certify that constraints and rules of the technical platforms are implemented in the customer view of a specific project, otherwise "adhoc" solutions will occur.
- Use view-specific ICT-tools and focus on reducing information that needs to be handled between them. This way of working will also conceal sensitive company knowledge.

One essential obstacle to overcome is that a company must select a specific market when developing a building system that will be advantageous from an industrialised point of view. This can be difficult due to the volatile conditions prevailing in the construction industry. Therefore the flexibility of the technical platform, i.e. the possibility of configuring the platform according to customer preferences without violation the production system is of great importance.

In mass production industries modularisation has played a prominent roll when structuring products that can embrace different customer needs, maintaining the level of productivity. In construction industry modularisation is a strategy to move from a craft-based operation to a more industrialized assembly process where productivity benefits can be used to get competitive advantage. The offsite production of prefabricated sub-assemblies is a first step, but modularisation must be realized carefully since the strategy influence the possibility of customisation. I believe that future work will focus on modularisation on a smaller scale, e.g. possibilities of customizing "walls in walls" still pushing the decoupling point further to the end customer, making the production more standardised. In this work of redesigning, modularizing known technical solutions, the AEC consultant will have a major role in the development of configuration tools. The future AEC "system integrators" will take the role of designing, marketing and providing the service rather than producing the product (Höök 2005). These systems integrators can also promote open building systems with exchangeable modules competing on a future more competitive market.

Paper 1, 2 refers to specification processes with the decoupling point named "select variant". These ICT-tools can be developed and used only by the company's organization which owns the entire process. The limited customization possibilities make these building systems suitable for the end customer configuration using web-enabled configuration systems. Paper 3 and 4 are working with ICT tools supporting the specification process named "configure to order" and needs parametric design tools that can be incorporated early in the configuration process, making it able to manage the information flow upstream and downstream. Referring to Baldwin and Clark (2000), modules can be developed to become "an abstraction and an interface". The proposed solutions showing the boundary condition for the architect working in the customer view do not expose the technical solution of the different modules. The interfaces can be designed with specific identities, see figure 11, assuring that the configuration is done according to module constraints of the building system, concealing and protecting the technical solutions in the customer view. This will be important in the development of open building systems where the architect can select modules on the open market that provide the best solution for the customer.

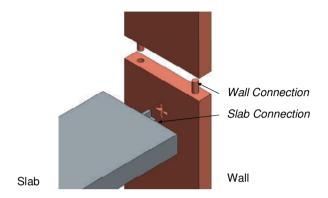


Figure 11: Interfaces with specific identities assuring that configuration of the project is done according to interface constraints.

There is a gap between building system development and the unique project configuration. I believe product platform implementation in the construction industry needs new tools supporting the development and configuration of building systems. This work need to be supported by PDM/PLM systems and structured work processes and design feedback loops to enhance quality and ensuring that the product is properly constructed. It's even more important that proposed solutions need to be verified and certified by the company. This way of working will also address new tasks for employees, such as configuration manager, controlling that projects are configured according to system constraints. Also, other business models needs to be reviewed supporting a more performance based and product oriented way of doing business.

5.4 Further research

In this thesis one possible solution of the exchange of information upstream and downstream in the configuration of a project was incorporated into a demonstrator were module objects was used in the design. Interviews with architects have shown that they rather work with free form objects and then check them against the building system, otherwise they might "lose their creative thinking" as one of the interviewed architect proclaimed. The search for better architectural tools is therefore needed.

Further research will focus on deepening the work with configuration processes by finding methods how to implement product platforms and how the processes can be supported by IT-based tools. The research will focus on three areas in particular;

- Methodologies that can be used in the development of a product platform.
- ICT-tools and working methods that can manage the information integration between tools used in the development of systems and the configuration of projects.
- From studies and interviews with architects, propose and develop better solutions for architectural configuration tools in the customer view.

6 REFERENCES

- Ackoff, R. I. (1999). *Ackoff's best His Classic Writings on Management*, NY: John Wiley & Sons Inc, New York.
- Adler, P. (2005). *Bygga Industrialiserat*, Svensk Byggtjänst AB, Stockholm. (in Swedish).
- Akao, Y. (1990). Quality Function Deployment QFD Integrating customer requirements into product design, Productivity Press.
- Anderson, D. M. and Pine, B. J. (1997). *Agile product development for mass customization*, Irwin, Chicago, il.
- Andersson, A., Apelberger, L., Molár, M. (2010). Erfarenheter och effekter av industriellt byggande i sverige, *technical report 0905*, fou-syd. (in swedish).
- Apelberger, L., Jonsson, R., Åhman, P. (2007). Byggandets industrialisering nulägesbeskrivning, *technical report 0701*, fou-väst. (in Swedish).
- Avison, D. E., Lau, F., Myers, M. D., and Nielsen, P. E. (1999). Action research, *Communications of the ACM*, vol. 42, no. 1
- Baldwin, C. and Clark, K. (2000). Design Rules, The MIT Press.
- Bertelsen, S. (2005). Modularization –A Third Approach to Making Construction Lean? *Proceedings of the 13th Annual Conference of the International Group for Lean Construction*, Sydney, Australia.

- Chalmers, A. F. (1999). What is this thing called science?, 3rd edition, hackett publishing company inc.
- Deepak, K., Chen, W. and Simpson, T. W. (2006). A market-driven approach to the design of platform-based product families, *American Insitute of Aeronautics and Astronautics*, pp. 1-25.
- Duray, R. (2002). Mass customization origins: mass or custom manufacturing? *International journal of operations & production management*, pp. 314-328.
- Duray, R., Ward, P. T., Milliam, G. W., Berry, W. L. (2000). Approaches to mass customization: configurations and empirical validation, *Journal of Operations Management 18*, pp. 605-625.
- Eastman, C., Techolz, P., Sacks, R., Liston, K. (2008). *BIM Handbook: A Guide to Building Information Modeling*, John Wiley & Sons Inc, New Jersy.
- Ekholm, A., Häggström, L., Tarandi, V., Thåström, O. (2000). Application of IFC in Sweden phase 2, *Working report A15*, The Swedish Building Center.
- Ekholm, A., Jönsson, J-A., and Molnár, M. (2008). Nyttan för byggbranchen En väg till effektivisering och industrialisering av byggindustrin, *Technical report*, Boverket, (in Swedish).
- Ekholm, A., and Molnár, M. (2009). ICT development strategies for industrialization of the building sector." *Itcon*, pp. 429-444.
- Ericsson, A., Erixon, G. (1999). *Controlling Design Variants: Modular Product Platforms*, Modular Management AB and Society of Manufacturing Engineers, New York.
- Erixon, G. (1998). *Modular Function Deployment: A method for product modularization*, doctoral thesis, dep. Of manufacturing systems, royal institute of technology, Sweden.
- Gerth, R. (2008). En företagsmodell för modernt industriellt byggande, licentiate thesis, kth, Sweden. (in Swedish)

- Gilmore, J. H. and Pine, J. B. (1999). *Markets of One*, Harvard Business School Press, Boston.
- Gross, M. D. (1996). Why can't CAD be more like Lego? CKB, a program for building construction kits, *Automation in Construction 5*, pp. 285–300.
- Halman, J. I. M., Voordijk, J. T. and Reymen, I. M. M. J. (2008). Modular Approaches in Dutch house Building: An Explanatory Survey *Housing Studies*, 23(5) 781-799.
- Hansen, B. L. (2003). *Development of Industrial Variant Specification Systems*, Ph.D. thesis, Department of Industrial Management and Engineering, Technical University of Denmark.
- Horsman, W. M. (2008). *Botrender 08: en rapport om framtidens boende*, Tyréns AB. (in Swedish).
- Hvam, L., Mortensen, N. H., Riis, J. (2008). *Product customization*, Springer-Verlag Berlin And Heidelberg,
- Höök, M. (2005). *Timber Volume Element Prefabrication: Production and market Aspects*, Licentiate Thesis, Department of Civil and Environmental Engineering, Division of Structural Engineering Timber Structures, Luleå University of Technology.
- Jensen, P., Olofsson, T., Johnsson, H. (2010). Configuration through parameterization of building components, *Submitted may 2010 to Journal of Automation in Construction*.
- Johnsson, H., Persson, S., Malmgren, L., Tarandi, V., Bremme, J. (2006). ITstöd för industriellt byggande i trä, department of civil and environmental engineering, division of structural engineering, Luleå University of Technology. (in Swedish).
- Jose, A. and Tollenaere, M. (2005). Modular and platform methods for product family design: literature analysis, *Journal of Intelligent Manufacturing 16*, 371-390.
- Josephson, P-E. and Saukkoriipi, L. (2005). slöseri i byggprojekt- behov av förändrat synsätt, *Technical report 0507*. Fou-väst, (in Swedish).

- Jørgensen, K. A. (2001). Product Configuration Concepts and Methodology, Manufacturing information, Systems Proceedings of the Fourth SME International Conference.
- Jørgensen, K. A. (2005). http://www.iprod.auc.dk/~kaj/documents/common/productconfigurationandproductfamilymodelling.pdf (accessed 2010 06-02).
- Kunz, J. and Fischer, M. (2009). Virtual Design and Construction: Themes, Case Studies and Implementation, CIFE Working Paper #097, Version 10, Stanford university.
- Lennartsson, M. (2009). *Modularity in Industrialized Timber Housing, A Lean Approach to Develop Building Service Systems*, Licentiate thesis, Department of Civil and Environmental Engineering, Division of Structural Engineering, Luleå University of Technology.
- Lessing, J. (2006). *Industrialised House-Building*, licentiate thesis, dep. Construction sciences. Lund institute of technology, Sweden.
- Marion, T. J., Freyer, M., Simpson, T.W., Wysk, R. A. (2006). Design for mass customization in the early stages of product development, *Proceedings of IDETC/CIE*, Pennsylvania, USA.
- Mark, V. and Ishii, K. (2002). Design for variety: developing standardized and modularized product platform architectures, *Research in Engineering Design 13*, pp. 213–235.
- Nanua, S., Ding, S., Jagirdar, R., and Basil, E. A. (1997). A knowledge engineering framework for rapid design, *Computers and Industrial Engineering*, Vol. 33, pp. 345-348.
- Nassare, K., Thabet, W., Beliveau, Y. (2003). Building assembly detailing using constraint-based modeling, *Automation in Construction* 12, pp. 365–379.
- Norberg, H. (2008). On-Site production synchronisation: improving the resource-flow in construction projects, Licentiate thesis, Department of Civil and Environmental Engineering, Division of Architecture and Infrastructure, Luleå University of Technology.

- Olofsson, T., Jongeling, R., Toolanen, B., Woksepp, S. (2007). Project environment and process design of building projects supported by virtual design and construction methods, *CIB 24th w78 conference*, pp. 233-238, Maribor, Slovenia.
- Olofsson, T., Cassel, E., Stehn, L., Ruuth, S., Edgar, J-O., Lindbäck, S. (2004) (in swedish) produktmodeller i ett flexibelt industriellt byggande, *Technical report 2004:06.* eBygg-Center for Information Technology in construction.
- Pazlar, T. and Turk, Z. (2008). Interoperability in practice: Geometric data exchange using ifc standard, *itcon vol 13*, pp. 362-380.
- Pine, J. (1993). *mass customization: the new frontier in business competition*. Boston: Harvard business school press.
- Racz, T. and Olofsson, T. (2009). Interoperability challenges of an engineering software provider, *Proceedings of the 26th International Conference on IT in Construction and 1st International Conference on Managing Construction for Tomorrow*, Istanbul, Turkey, pp. 275-285.
- Robson, C. (2002). Real world research: a resource for social scientists and practitioner-researchers, oxford, Blackwell.
- Samuelson, O. (2003). *IT-användandet I byggande och förvaltning*, licentiate thesis, dep. Industrial Economics and Management, royal institute of technology, Sweden. (in Swedish).
- Sacks, R., Eastman, C. M., Lee, G. (2003). Process improvements in precast concrete construction using top-down parametric 3-d computer-modeling, *PCI Journal*, 48:3, pp. 46-55.
- Sandberg, M., Johnsson, H., Larsson, T. (2008). knowledge-based engineering in construction: the prefabricated timber housing case, *Itcon vol 13*, pp. 408-420.
- Sandberg, M. (2007). *Design for manufacturing, methods and applications using knowledge engineering*, doctoral thesis, dep. Of applied physics and mechanical engineering, division of functional product development, luleå university of technology.

- Simpson, T. W. (2003). Product platform design and customization: Status and Promise, *Artificial Intelligence for Engineering Design*, 18, 3-20.
- SOU (2002). Skärpning gubbar!, Om konkurrensen, kostnaderna, kvaliteten och kompetensen i byggsektorn, SOU 2002:115, byggkommissionen, Miljö och samhällsbyggnadsdepartementet, Stockholm, Sweden, (in Swedish).
- Sundström, P. (2010). *Utvärdering av ett byggsystem: Synpunkter från arkitekter*, M.Sc. Thesis, Division of Structural Engineering, Royal Institute of technology, (In Swedish), To be published.
- Ulrich, K. (1995). The role of product architecture in the manufacturing firm. *Research Policy 24 (3)*, pp. 419-440.
- Veenstra, V.S. Halman, J.I.M. and Voordijk, J.T. (2006). A methodology for developing product platforms in the specific setting of the housebuilding industry. *Research in Engineering Design*, 17(3) 157-173.
- Voordijk, H., Meijboom, B. and de Haan, J. (2006). Modularity in Supply Chains: A Multiple Case Study in the Construction Industry. *Int. J. of Operations Production Management*, 26(6) 600-618.
- Wallén, G. (1996). Vetenskapsteori och Forskningsmetodik, lund, studentlitteratur.
- Widerberg, K. (2002). Kvalitativ forskning i praktiken, lund, studentlitteratur.
- Wikberg, F., Ekholm, A., Jensen, P. (2009). Configuration with architectural objects in industrialised house-building, *CIB W78*, Istanbul.
- Wikforss, Ö. (2003). *Byggandets Informationsteknologi*, svensk byggtjänst AB, Alqvist och Wiksell tryckeri, Uppsala. (in Swedish).
- Winch, G. M. (2003). Models of manufacturing and the construction process: the genisis of re-engineering construction, *Building Research and Information*, 31(2), pp. 107-118.
- Woksepp, S. (2007). Virtual reality in construction: tools, methods and processes. Department of civil, mining and environmental engineering. Luleå, luleå university of technology.

- Yin, R. K. (2003). *Case study research, design and method*, 4rd edition, sage publications inc.
- Zhinling, M., Heng, L., Shen, Q.P., Yang, J. (2004). Using XML to support information exchange in construction projects, *Automation in Construction* 13, pp. 629–637.

Appendix	Α.	sales	office	questioni	naire
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APPENDIX A; SALES OFFICE QUESTIONNAIRE

Frågeställning försäljningsavdelningen

Syftet:

Att med önskemål och krav från specifikt kundsegment se hur väl byggsystemet uppfyller dessa.

Genomförande av analys:

Krav och önskemål från kund skall omvandlas till ett "typhus" som skall pressenteras för konstruktionsavdelningen på huvudkontoret. Konstruktionsavdelningen kan utifrån detta hus förklara begränsningar och svårigheter i deras byggsystem som uppkommer för att lösa krav och önskemål från kund.

Genomförande av Intervju:

Dessa frågor skall endast ses som ett stöd i diskussionen och kan förhoppningsvis förtydligas under mötet.

Frågeställning:

- 1. Hur ser säljningsförfarandet ut vid möte med ny kund?
- 2. Vilken är det tänkta kundsegmentet och hur ser den figurerade kunden ut?
- 3. Vilken typ av hus säljer ni? Typhus, kundanpassat?
- 4. Hur förmedlar ni företagets anpassnings begränsningar?
- 5. Är pris den överordnade säljtaktiken?
- 6. Vilka är de vanligaste säljargumenten för ert företag, vad skiljer er från övriga företag?
- 7. Vilka krav ställer kunden på flexibilitet vad det gäller husets utformning?
- 8. Finns några viktiga designkriterier som många köpare frågar efter?
- 9. Finns krav på tillbyggnadsmöjlighet?
- 10. Hur viktigt är tidsperspektivet? Vad anses som en rimlig tid att få ett hus inflyttningsklart?
- 11. Har förseningar i leverans någon betydelse för val av hus leverantör vid försäljning?
- 12. Hur sker uppföljning ut av levererade hus?

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Life is a puzzle; these are some of them...



REDUCING COMPLEXITY OF CUSTOMIZED PREFABRICATED BUILDINGS THROUGH MODULARIZATION AND IT SUPPORT

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ABSTRACT

Many companies in Sweden using prefabricating strategies are currently meeting the ever increasing customer requirements with ad-hoc solutions that do not fit their production system. This is causing bottlenecks and lower profit margins as a consequence. One solution to the problem is to re-engineer their building systems according to modularization principles used in the manufacturing industries, which have adapted their production to be able to meet mass-customization.

This paper describes the first part in study of modularization of building systems and if methods used in the manufacturing industry can be adapted to the building industry.

The Swedish construction industries using prefabrication strategies are mainly project oriented, and needs to develop a more product oriented development process to benefit from the values that modularization can give. It is also obvious that it is impossible to introduce modularization methods used in manufacturing industries if design requirements are incomplete or changing from project to project. It is therefore essential that the product owner owns the whole process as well. Varying customers' demands can to some extent be handled using modularization principles. However, we don't believe that one solution fit's all; therefore it is essential to target a specific segment of the market. The cost for the development of such modularized building system for the targeted segment of customer must be evaluated against the possible market share.

KEYWORDS

Modularization, standardization, prefabricating, Quality Function Deployment (QFD), Modular Function Deployment (MFD).

1. INTRODUCTION

Many of the Swedish prefabrication single-housing industries were established in the mid 60's. Prefabricated houses now dominate the single-house market in Sweden with a market share of as much as 80%. In the 60's and 70's the customer demands were low and architectural designs and technical solutions were standardized (Höök 2005). In the beginning of the 80's competition in the single-housed market inclined and companies were facing new rivalry due to increasing demands on customized solutions, (Hill 1994). Initially well designed standardized technical solutions were transformed using "ad-hoc" solutions necessary to customize the house according to customers needs. This was, according to Brege (2008), one of the main reasons to the fall in profits in the prefabricated single-housing industries in the 80's.

Josephson and Saukkoriipi (2005) states that as much as 35% of the total production costs can be identified as waste in traditional on-site production of apartment blocks. This has inspired several constructions companies in Sweden to implement building systems for the production of apartment buildings. However, the question arises how the building system can be customized in order to be competitive on the market? Adaptation to the increasing demands for customisation is facing many industrial sectors around the world and, according to Ulrich and Eppinger (2008), mass customization methods can be used were the customer can tailor the product according to his/her own needs. Modular Function Deployment (Erixon 1998), is one strategy that can be adapted to prepare a product family for mass customization. One big difference when referring to methods used in the manufacturing industry is that they are developed for product oriented processes where a decentralized product development process are common (Johnson et. al 2006). The building industries are conventionally project-oriented, and methods that are used in the manufacturing industry must be adapted to the building industries way of working. According to Lessing (2006), the focus on the individual project in the building industry has often led to a fragmentation in the process with little continuity and low productivity development. Also, no single actor owns the whole process as opposed to the manufacturing industry, Nordstrand (2003).

The purpose of this paper is to explore methodologies for customization used in the manufacturing industry that in a structured way can evaluate customers demand against the possibility of customization of a standardized building platform.

2. THEORY

2.1 MODULARIZATION

Modularization is currently a key concept for customization in the manufacturing industry to reduce complexity. Advantages in standardized and rationalized product structures, makes it possible to customize flexible solutions (Ulrich and Eppinger 2008). According to Erixon (1998) modularization is, "decomposition of a product into building blocks (modules) with specified interfaces, driven by company - specific reasons". The building industry in general does not have the same interpretation of modularization, which can be confusing. Often modularization is referred to as "standard building elements or volumetric pre-assemblies" (Höök 2005). Arranging the main assembly station with several short module assembly lines makes the production system easy to understand. "Factory in factory" increase the meaning and personal satisfaction of the production staff due to better understanding of the production system (Erixon 1998). Baldwin and Clark (2000) states that humans needs to divide complex systems to be able to understand and solve problems. When a system is divided into smaller parts, the complexity of the minor parts can easier be solved. The complexity of the system can be concealed behind "an abstraction and an interface" (Baldwin and Clark, 2000). The abstraction represents a module with a certain function that can be combined with other modules using a standardized interface. In the manufacturing industry product lead time is vital: "Six months delay in product introduction results in 33% less profit over 5 years while on time introduction but 50% development expense overrun only result in 4% less profit over the same period" (Charney 1991). If new house "models" can be introduced faster with the modular building system, the benefits of following market trends would be noticed also in the building industry. It can also reduce components in stock with less capital assets in use.

2.2 MFD – A METHOD FOR MODULARIZATION

Modular Function Deployment or MFD is a method that systematically divides products or families of products into modules, based on five key steps. In step 1 the customer needs are recognized by using the Quality Function Deployment (QFD) method, (Akao 1990). After the product properties are determined from the QFD analysis, technical solutions that meet these needs are developed in step 2. When technical solutions

are chosen, a module grouping process is performed in step 3 creating a Module Indication Matrix (MIM). This step identify "module drivers" that arrange the technical solutions into similar characteristics. The new concepts and the technical solutions are evaluated using an evaluation chart, step 4, where the identification and evaluation of module interfaces will be an important factor for which concept to select. When the modules are found they can be improved developing module variants with the same interface without affecting other parts (modules) of the product. Step 5, the design process or development of modules/ module variants can then be structured with methods like Design for Manufacturing/ Assembly (DFMA), (Erixon 1998)

2.3 OFD - TRANSLATING CUSTOMERS NEEDS INTO PRODUCTS

Designing products that are focused on customers needs is essential to sustain competitive advantage. Mapping the customer needs against the product properties, well defined methods have been developed in industries around the world. Perhaps the most frequently used is called Quality Function Deployment (QFD) that emerges from Japan, (Akao 1990). In the year of 1966 QFD was conceptualized for the first time, as means for introducing customer needs early in the design process. QFD arises from mainly two issues that automobile industries in Japan had. First, design quality started to have a greater determining factor, but there were no books available in those days. Second, OC (Quality Control) process charts were established after the products were built, which made it hard improve the process (Akao 1990). To be able to find the customer needs and structure them, tools called affinity diagrams can be used. The voice of the customer can then be arranged in hierarchy levels were the first level defines the idea, next level provide definitions for the primary level, the third level describes the details for the second level etc. This can also be described in a tree diagram (Eldin and Hikle 2003). When the customer requirements are found a house of quality (HoQ) matrix can be formed and the product properties emerge, see figure 2. The relations are determined and marking scale can be used to define how strong the relationships are, this formation is mainly done by individual judgments rather than concrete solutions. The product properties are weighted and normalized to find the most important properties. The work of finding customers needs and turning them to product properties are often done by a QFD-team were all disciplines are involved. In traditional procurement systems, when design and construction is done by different participants, the general success in using OFD methodology can create a problem. In figure 1, the construction industry, with the project centric way of working is defined. Different parties are responsible for different parts of the project, and "Cross-functionality" often used when conducting a QFD can be hard to achieve. The methodology of QFD can be suited for projects/ products were a single part is responsible for every phase and the function requirements can be well defined in an early stage, and not as a parade of trades. (Dikmen et al. 2004).

In the building industry much work in identifying needs have been concentrated on the geometrical shape of the building and arrangement of rooms; often these improvements have been performed by using Quality Function Deployment in the design phase (Gargione 1999, Ozaki 2002). Not much work has been conducted, to the authors' knowledge, using QFD as a general tool focused on the requirements from a customer's perspective on the product properties of a building system.

2.4 PRODUCT CONFIGURATION AND PRODUCT MODELS

The main advantages in modularisation is that despite the end product can vary in shape and functions, the design and production of components and modules within a product family are the same. The design phase is replaced by a configuration phase where the product is customized by selecting an appropriate set of module variants from the product family. From an information management point of view, this means that the product model used in the configuration phase must also be modular, (i.e. contain all modules and variants of the modules). The result of the product configuration is a specific product model that contains all information for production of the customized product (Jørgensen 2008).

The modularity of the product model can be divided in different types (Gerth 2008):

Based on structure: Alternative component models where the customer selects one alternative of the companies product model alternative or free selection of components where the customer have freedom of selection of components/modules in a so called addition process of parts not compulsory for the product. The product can then be more customized by adding additional functionality.

Based on attributes: Specific components/modules can be varied through the use of attributes, either
by the use of enumerated or numerical values. Example, color on a module (red, green, blue etc.) or
the length of a specific component (6 m).

3. THE PRODUCT CENTRIC BUILDING PROCESS

The Swedish building process is generally divided in several steps involving numerous of participants, (Nordstrand 2003). The participants involved are working by them selves with no or little contact to each other, and they are often dissolved when projects are finished. What separates the industrialized building process from the on site construction projects is that they own most of the disciplines and process, still they work on a project basis see figure 1.

To take advantages of modularization techniques it is necessary to go from project focus to product focus. In the future modular building process, figure 1, it is essential to separate product design from project, only then it is possible for companies to gain advantages in continuous improvements of product developments. Modularization methods based on customer focus and process techniques can then be feasible (Lessing 2006).

"The key, many in modular bridge industries say, is for engineers and contractors to start thinking of bridges in terms of products rather than projects." (Shaker and Greenwald 1994).

It is also important to find a market "niche" for the company to be able to meet particular group of customer requirements, (Ozaki 2002). Thereafter the design of the product platform can start since the solution will be based on requirements of the target customer. Time from separate project can then be devoted on product development where the individual project using a configuration process supported by the technical platform. When the organization is arranged as the lower part of figure 1, IT-support and configuration tools will be necessary to implement to organize the building systems and the product structure into interchangeable modules and module variants (Johnson et al. 2006). If the building system is not organized into design rules and configuration patterns much of the ICT support will lose its purpose. Problems that otherwise will be solved using "ad hoc" solutions and many cases special built products", (Erixon 1998).

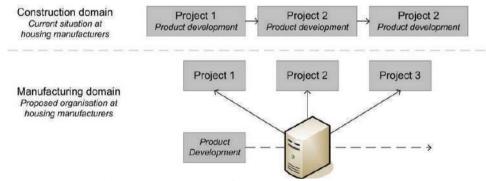


Figure 1: Project and product focused processes. (Johnson et al. 2006).

4. CASE STUDY- SMALL PREFABRICATING COMPANY

The purpose of the case study is to illustrate the possibility to apply QFD in construction. The study is made on a part of an already designed building with the purpose of translating demands and needs to design requirements for the specific building part. The next step would be to implement modularization strategies in future designs of the building.

4.1 THE COMPANY IN THE CASE STUDY

The company involved in the case study is working with design and constructing of new small houses for family use. According to the owner, "customers wish to buy a well design/ architect drawn house filled with dreams". Their new approach to the market is that they are delivering new designed houses in what they call a

collection, 3-5 new types of houses every second year. They deliver complete material and components needed above the foundation including assembling instructions. The assembly of the house is left to be done by the customer. The material is delivered pre-cut together with components, such at fittings kitchen utilities, in a container and with little or no prefabrication what so ever. To sustain competitive advantages, the company needs to modularize the technical solution to find carryover solutions between collections.

4.2 TRANSLATING NEEDS TO PRODUCT PROPERTIES

In every new product design, you have to find the customers needs and what the product is supposed to deliver and this at low cost in order to get an "economic success", (Ulrich and Eppinger, 2008). This first step, as presented previously, can be evaluated using QFD to map customers need against product properties.

The problem is that the overall product properties are the same for most buildings, a building are supposed to withstand water and wind etc. and characteristics that separate the different companies and building systems from each others is the architectural design. Therefore, companies need to select a particular segment of the market in which a specific group of customers are the target for the QFD analysis (Ozaki 2002). The customers in focus, market "niche", could be the architectural design or "low price" that a company are focusing on. If design is the competitive edge, the QFD will be directed on how the technical solutions can solve the specific architectural design. As an example if the target customers are interested in "old fashioned" architectural design, roof construction will most likely be steep with big bases of a roof. On the other hand, the technical solutions for a flat roof "with a contemporary design" will be different. Market analysis is therefore critical in any new product design.

The other benefit of targeting a specific group of customer is that the product development costs for the architectural and technical design can be shared by a larger volume of houses. When technical solutions can be reused within a specific collection and carried over to the next generation of collections through modularisation, the development costs/per house can be reduced even more. Also, this would most probably lower the production cost over time and give opportunities for industrialized production of certain parts of the building.

The target group in the case study can be said to be the design aware customer who want to own a unique architectural designed building. However, the price matters. From the market analysis, the proposed solution was to engage a known architect to do the design and as a compromise between uniqueness and cost. The design is only going to be used for a certain collection of houses over a limited time. This type of trade marking a product is common in other sector and a well-known example is H&M who uses world famous designer to design specific collections of clothing in a limited edition.

In this paper we will use the roof design proposed by the architect as an example, of how we can translate the functional requirements to roof properties. The requirements are listed on the left side and product properties on top of the OFD diagram in Figure 2.

The requirements part has been divided into 4 categories that will affect the technical design:

- Standard specifications, i.e. regulations from national authorities.
- Market niche, as interpreted by the architect
- General demands, i.e. from the owner
- Production demands.

The link between requirements and product properties is indicated with circle in the QFD diagram. The product properties can now be used to guide the design of technical solutions and abandon old solutions that would be used otherwise.

	FLAT ROOF	Product property	Construction part must be able to resist a moment of at least XX kNm	Construction part must be able to resist a shearing force of at least XX kN	Construction may not deflect more then XXmm	Diffusion leakproof construction	Have a thermal resistance of minimum 0,02	Building part may not have any water Leakage	No burnable material on the inner side of roof	Roof surface must be made of material that are approved by standard regulation	Max weight of 150kg each construction	Max length of construction part 20 feet
	Must be able to take care of snow given		0	0	0							- 1
STANDARD	by standard specifications			\cup	0							
SPECIFICATION	Must be able to take care of wind given by standard specifications		0	0	0							
DKK, BBK, ETC.	No deflection bigger then length/150 in the serviceability limit state		0	0	0							
()	Building part must have 5meter bearing distance		0	0	0							
SPECIAL	Construction part mustn't be thicker then 0,5m		0	0	0							
MARKET	Must have a flat surface on the inner side				0							
NICHE.	The incline of the building part must be 10 degree									0		
	Possible to integrated spotlights in the inner roof					- 0		n s	0			
51-01-9-422-6 x52-m-23300 00	Low energy loss by leakage ore heat radiation						0					
GENERALL DEMANDS	No mould in construction part					0		0				
termopos utrattettisto	No water inside the construction part					0		0				
PRODUCTION J	Must be able to place in a container							30 S				0
DEMANDS	At most 3 persons assembling the house										0	

Figure 2: Example of QFD executed on the roof-construction

4.3 RESULTS FROM THE QFD-ANALYSIS

The product properties that were extracted from the QFD matrix, showed the possibilities to clarify customer needs that otherwise would be hard to take notice of. For example the early design of the roof construction done by the architect, the ceiling was inclined. But there were no product requirement that specified this from the customer point of view. This construction solution imposed the walls to be cut with an angle of degree; and the reason to separate the walls on the gable flanged end from the rest. By making the ceiling of the house horizontal, the walls could be made in the same height and therefore dramatically reduce product parts. It is easy to see that these kinds of standardizations can in a following investigation of modularization techniques help to locate possible parts to standardize, taking in account only those aspects that are essential for the customer. For example; if the company wish to generate a two story building in the next collection, there will be no difference between the walls on the first floor and the second, this when walls can be made in same heights and the interface are the same. Another important thing that was found when conducting the QFD analysis on the construction part was that the conceptual design did not support the installation of spotlights in the ceiling without going through the vapour barrier, even though spotlights in the ceiling was important for the targeted customers. Design errors like these would most likely have increased the production cost. Performing the QFD that might seem unnecessary and time consuming can easily be justified.

The case study company has built three exhibition houses with the architect's early construction design. Thus the comparison of the total building costs for the new building system cannot yet be evaluated.

4.4 MODULARIZATION PROCESS

In the manufacturing industry it is common to produce a product that is supposed to perform a certain duty. A car ought to transport something somewhere; a stapler is used to make holes in a piece of paper. The purpose of the product creates a variety of function-requirements. The identified function requirements are then structured in a way that leads to desired solution(s). From a modularisation point of view, the product should be designed in such a way that there exist a one-one relation between each functional demand – and the technical solution. Then, new functionalities can be added, by adding a new module to the existing set of modules. This type of design is common in the software industry (Baldwin and Clark 2000).

A house has also many different functions; however the technical solutions providing these functionalities are more difficult to separate from each other. The house shall offer cooking possibilities, supply with shelter, the rooms must supply users with electricity, the air-flow in the building must be in certain ways, etc. Therefore, a QFD study on the building as hole with different levels of requirements is hard to do, especially when no specific group of customer is targeted. To manage all these different demands in different levels the interfaces between the typical solutions from the market analysis must be found and this can provide the possibilities to perform the product development on a certain construction part. After this is done the product design can be made using modularization methods like MFD. Figure 3 shows the general process and how QFD can be used in the product development process translating functional requirements from the market "niche", which later can be used in the MFD process finding modular products.

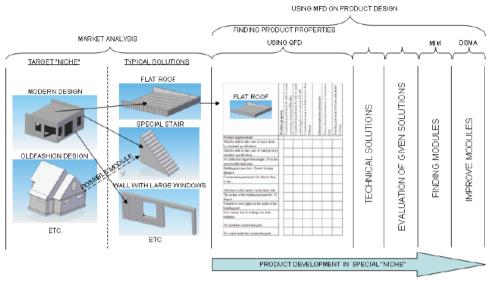


Figure 3: Product development of houses using modularization techniques.

In the product design phase the design properties are converted into technical solutions that are evaluated from a modularization perspective. When the modularization of the technical solutions starts (MIM), reason for modularization must be considered. The purpose in the case study is to minimize the design effort, the assembly instruction for the technical solutions for development of new collections. The building system need to be defined in such a way that interfaces between modules in a collection is the same. Also, if these interfaces can be used in the next collection, the probability is high that the design work can be limited to the development of new variants of the modules making the design work and production of the assemblies more rational. If a house is modularized to have different spans in the building then perhaps the thickness of the "framing of joists" must have different heights. If the heights are different then it would be hard to make the connection inside the house since the interface and structure between the walls inside the house would change. Instead of changing heights of the slabs, the interface imposed by modularization principals need to be inside the walls. This could according to Shaker and Greenwald (1994) instead be solved using several beams with the same height, where the varying requirements on the load capacity of the "framing of joists" can be met by increasing the number of beams in the construction.

5. DISCUSSION

Prefabricated house manufacturers are meeting an increasing demand for customizations and their current building systems need to be reengineered to meet the new market demands. The benefits from using standardized prefabricated building systems are slowly being diminished, since the common way to solve the customization today is to use "ad hoc" solutions. The problem has slowly emerged from the beginning of the 80's and many industries in the sector are facing the same problem trying to use a building system, not made for customization.

Some manufacturing companies have attacked these problems and being successful using modularization to adapt their product and production system for mass customization. Why can't construction industries work in similar ways? Much of this problem dissolves from the fact that manufacturing industries are product oriented whereas construction is project driven. Contractual forms and number of participants often working in separated phases over the project life has separated design from production. Ad hoc solution to please a specific customer are causing problem in the production phase. According to Erixon (1998); "the design phase can determine 75% of the production costs". This has led to methods like MFD to put more emphasis on "Design For Manufacture". The problem of not specifying the functional requirements also from a production perspective leads to designs not really adapted for the production system. Methods like QFD can

help to identify design properties that are vital both from a customer perspective and from a production system point of view. Methods like MFD can then be used to identify both process and product "modules" that can be re-used over time from project to project. However, it seems essential that the same actor in the building project is also the owner of the product. The most likely candidate is the building constructor making him the process owner. Then the benefits (but also the risk) of investing in new building system can be calculated over a time span longer than the individual project. Today, you often hear things like "this building is so unique and will only be built once" but many of the parts in the "unique" building are used over and over again in many construction projects.

In the case study analysis it was clearly observably that the actual product properties from which the design is based on can easily be extended adding more functional requirements such as production needs. Often, these step is omitted in normal design in the building industry, since the designers needs to deliver a technical solution on a short notice.

From the functional requirements given by standard regulation, customer demands and production constraint (built by at most 3 persons, delivered in a container etc.), it was relatively easy to specify the product design properties. They gave a number of technical possible solutions that could be screened by the principles of modularisations. A possible modular solution was proposed that can be varied within the actual collection of houses. Also, the QFD method makes it possible to see reason for abandoning traditional technical solutions that would otherwise be used. Construction industries products (houses) are mainly different in the architectural design, and it is essential to have this in mind. Manufacturing industries are mainly separated by their technical solutions.

We believe that going from project design to product design, modularization is essential to meet the customer future demands and at the same time take the advantages of carry over technical solutions from "project" to "project". Also, this makes it more motivating to use state of the art IT technologies to speed up the design and production phase, i.e. shortening the customer lead time from order to delivery. This is believed to be a major factor in a company competitive edge. (Mortensen et. al 2007)

6. CONCLUSION AND FUTURE WORK

Swedish Construction Industries are mainly project oriented, and needs to go to a more product oriented development to benefit from the values that modularization can give. It is also obvious that it is impossible to introduce modularization methods used in manufacturing industries if design requirements are incomplete and changing from project to project. It is therefore essential that the product owner owns the whole process as well. Varying customer's demands can to some extent be handled using modularisations principles. However, we don't believe that one solution fit's all, therefore it is essential to target a specific segment of the market. The cost for the development of such modularized building system for the targeted segment of customers must be evaluated against the possible market share.

It has also been noticed that QFD and MFD are possible methods to develop such a building systems.

In future work we will study modularization and the adaptation of methods like MFD in the construction industry. Can this method be used to re-engineer existing non-flexible building systems in the building industry in Sweden?

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REFERENCES

Akao Y (1990) Quality Function Deployment QFD, Integrating customer requirements into product design, Productivity Press.

Baldwin C. and Clark K. (2000), Design Rules, The MIT Press

Brege S. (2008), Presentation during workshop for Lean wood engineering program.

Department of Management and Engineering. Linköping university

Charney C (1991) "Time To Market. Reducing Product lead Time", SME Dearborn,

Michigan, USA.

Dikmen I, Birgonul M. T, Kiziltas S (2004) Strategic use of quality function deployment (QFD) in the construction industry, Building and environment 40 (2005) 245-255

Eldin N, Hikle V (2003) Pilot study of Quality Function Deployment in construction projects, Journal of construction engineering and management, pp 314-329

Erixon, G. (1998), Modular Function Deployment – A Method for Product

Modularization, Doctoral Thesis, Dep. of Manufacturing Systems, Royal Institute of Technology, Sweden.

Gargione L. A. (1999), Using Quality Function Deployment (QFD) in the design phase of

an apartment construction project, Proceedings IGLC-7, Berkeley, USA

Gerth R. (2008), (In Swedish). En företagsmodell för modernt industriellt byggande, Licentiat Thesis, KTH, Sweden, to be published,

Hill T (1994), Manufacturing Strategy - Text and Cases, Richard D. Irwin Inc.

 $Hvam\ L,\ Mortensen\ N.\ H,\ Riis\ J\ (2007)\ Product\ customization,\ Springer-Verlag\ Berlin\ And\ Heidelberg$

Höök M. (2005), Timber Volume Element Prefabrication - Production and market

Aspects, Licentiate Thesis, Department of Civil and Environmental Engineering, Division of Structural Engineering - Timber Structures, Luleå University of Technology.

Johnsson H, Persson S, Malmgren L, Tarandi V, Bremme J (2006), (In Swedish), IT-stöd

för industriellt byggande i trä, Department of Civil and Environmental Engineering, Division of Structural Engineering, Luleå University of Technology.

Josephson, P.E. And Saukkoriipi, L. (2005), (In Swedish), Slöseri I byggprojekt- Behov av förändrat synsätt. Fou-väst, report 0507.

Jørgensen, K. (2001). Product Configuration - Concepts and Methodology. Manufacturing information Systems Proceedings of the Fourth SME International Conference.

Lessing J. (2006), Industrialised House-Building, Licentiate Thesis, Dep. construction

Sciences. Lund Institute of Technology. Nordstrand U. (2003), (In Swedish), Byggprocessen, Liber

Ozaki R. (2002), Customer-focused approaches to innovation in housebuilding,

Construction Management and Economics, Volume 21 pp 557-564

Shaker S. M., Greenwald J. H. (1994), Modular Evolution, ProQuest Science Journals, pp 64-67.

Ulrich K. T. And Eppinger S. D. (2008), Product Design and Development, McGraw-Hill International edition.



PRODUCT MODELING OF CONFIGURABLE BUILDING SYSTEMS – A CASE STUDY

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SUMMARY:

This paper investigates a Swedish house manufactures building system regarding the documentation and information structures. The aim is to evaluate how product modeling technology can be used to facilitate product customization. By dividing the product in 4 different views the complexity of the product can be reduced and each view represents the interest of customer, engineering, production and assembly respectively. The analysis shows that the connections between the different views, i.e. the information transfer, is an area for potential improvements and little attention has been devoted to transfer information upstream from manufacturing and engineering to the customer view. The lack of information transfer can often lead to ad-hoc solutions in the customization process. We believe that successful cooperation and information exchange between these four views is the key to future development and customize-to-order configuration.

KEYWORDS: industrialized construction, modular houses, information management, building product model, product customization.

1. INTRODUCTION

Production methods of Swedish house manufacturers vary from almost manual carpentry to highly automated manufacturing units. Earlier studies in Sweden have concluded that information management in Swedish timber house manufacturing is relatively poor and similar to on-site construction, Johnsson et al (2006), Persson et al (2009). The information gaps between sales, engineering and production departments often lead to situations where customer requirements are implemented using ad-hoc solutions that are not suitable for the existing production system. Traditional methods and use of project oriented IT-tools do not support the industrialization and automation of the house manufacturing industry, Johnsson et al (2007). Therefore, new methods and IT systems need to be developed integrated in the design and production of manufactured houses.

Many of the developed building systems have evolved during decades and cannot easily be adapted to fluctuating markets. Also, the lack of proper description of the building system makes the system harder to adapt to volatile customers' requirements. The product documentation often consists of drawing files in CAD libraries (predominantly AutoCAD) that make the products difficult to use in a customization process. According to Nasereddin et al (2007), adequate documentation of the product structure and customization processes is essential for the productivity and quality of the end product. The "ad-hoc" customization of initially well-standardized technical solutions is one of the main reasons for the decreasing profits in the Swedish prefabricated single-house industry, Brege (2008).

Development of modularized product platforms is one strategy for mass customization, Erixon (1998). The customization process needs information of the product structure, its constraints as well as the customer requirements in order to develop a successful configuration and modularization strategy, Yang et al (2008).

2. OBJECTIVES AND METHOD

The objective of the study is to investigate how product modeling technology can be used by industrialized house manufacturers in the customization of a building system. More specifically three research questions are formulated:

- 1. How can an existing building system be documented using product modeling methodology to cover the process from sales to the realization of a customized building?
- 2. How well can the existing building system be adapted to customers' requirements?
- 3. How is the flow of information from sales to realization of the building affected by the use of product modeling technology?

An investigation of a Swedish company has been performed where three methods of collecting information were used for the case study of the building system in the research project:

- Studying drawings and documents of the building system as well as the production system
- Interviews with sales and engineering department
- Workshops with engineering department to verify the product model of the building system

The existing description of the building system is used as a basis for creating the product structure presented in section 4. From drawings and documents a first description of the product design and production constraints was established. This part of the study was performed with the intention to create a first product model of the case study building system. The information was then illustrated in product views, see section 4.4.1-4.4.4, which were used to refine and verify the product structure of the building system with the engineering department in a workshop. The refined version presented after the workshop is the version published in this paper.

Two methods were used to define a set of popular requirements from a typical customer used in the study described in section 4.5:

- Information gathered from a Swedish survey of housing standards, Horsman W. M. (2008)
- Interviews with the sales department in the company

3. THEORY

3.1 Information and product models

An information model represents a part of the real world, in some cases referred to as the universe of discourse, Björk (1995). All information models are unique, as well as the process of creating it, Schenck and Wilson (1994). According to Schenck and Wilson (1994), an information model should be precise, complete, non-ambiguous, minimally redundant and implementation independent.

Companies that develop, manufacture and sell complex products need to define and manage product information during all stages of the life cycle, Claesson et al (2001). These information models that contain data of both the product and the processes supporting the product's life cycle are generally referred to as product models. A building information model, BIM, is a product model defined for building products. A well known model standard for buildings is BuildingSmart, Industry Foundation Classes (IFC), BuildingSmart (2009). The team defining the set of rules used to interpret the data in the product model, i.e. the model schema, consists of product modeling experts and domain experts possessing knowledge of the product and the supporting life cycle processes. The definition of product model schemas often contains a mix of various methodologies, for example top-down and bottom-up in an iterative process, Hvam et al (2008), Schenck and Wilson (1994). There are several methods, which could be applicable for definition of product models in construction, Hvam et al (2008), Lee et al (2007).

According to Björk (1995), the creation of a product model for buildings starts by defining the classes of the main building parts and the systems they form, i.e. structural system, installation system etc. The next step is the definition of the most important attributes of these classes and the relationships between these object classes needed in many applications. A similar approach is suggested by Schenck and Wilson (1994), where basic classes and relationships often can be extracted from the domain experts by frequently used nouns and verbs, were nouns represent the physical objects and verbs represent the relationships between the objects.

There are aspects that have significance in the choice of information modeling language, Björk (1995):

- Capability for modeling the semantics of the universe of discourse without simplifications caused by the information modeling language
- Capability for modeling the designer's intents and aims
- Support for the evolutionary process of design (extendibility of the schema)
- Usefulness for the exchange of data between heterogeneous computer applications in construction
- Technical feasibility for implementation using current commercial software
- Realistic possibilities for achieving standardization (in terms of reaching consensus in standardization bodies and expenditure)

A popular language used in many product model applications such as the STEP and IFC model standard is the EXPRESS modeling language, Schenck and Wilson (1994).

3.2 Product configuration

Product configuration is described by Hvam et al (2008) as an effective mean of structuring products and standardization, but also a way of presenting the product for the customer. Also, the structuring of products in product models becomes a common view of the product ranges in the company that can be shared by the people involved in the support of the product life cycle, e.g. sales, design, production and maintenance. Before a configuration project is initiated, the following issues need to resolved, Hvam et al (2008):

- The range of products to be part of a configuration system need to be structured in some form of product structure. Often conflicting views exist in the company regarding rules, degree of detail etc., these issues have to be resolved before any product modeling initiative is launched.
- Companies also have to decide what parts of the product range that should be included in a
 product configuration system. Probably, not all products are suitable for configuration.
- The information needed for the product configuration project need to be collected. This information often resides in documents, CAD files and different type of management systems such as ERP, SCM and CRM as well as in the knowledge of product specialists in the company.
- How should product information be stored, updated and maintained? The product model will have
 to be constructed so that these parameters are effectively considered.

Leckner & Lacher (2003) pointed out that customer oriented product modeling is governed by the flexibility required in the product configuration process. They defined different types of flexibility or the degrees of freedom of a product:

- Alternative component model were the customer can choose exactly one from a set of exclusive alternative components;
- Optional component model where the customer can select optional components not obligatory for the product in an add-on configuration process;
- Attribute enumerated set model where the customer can choose a component with one value from a predefined set of possible values;
- Attribute numerical interval model where the customer can choose a component with one value
 within an interval boundary.

The result of a product configuration is a customer specific product model where the product properties and functions are determined and specifications of what modules and components will be produced and assembled are given, Jørgensen (2001).

3.3 Customer requirements

The increasing demands on products matching customers' individual preferences and tastes put pressure on manufacturing companies to offer more product varieties, Veenstra et al (2006). Still, the economical benefits of mass production need to be retained to keep the production cost at an acceptable level, Hofman et al (2006).

Since the cost of developing a building system is high, system analysis and customer surveys of the target market segments are important in the design of modularized product platforms, Bertelsen (2005). This approach is well known in the manufacturing industry but often foreseen in construction companies since customer requirements are treated only in the specific project and often specified by the client in a building program. A

product platform needs to be adapted to a variety of customers in the targeted market segment to be competitive. A number of methods have been developed to map customer demands against product properties. Quality Function Deployment (QFD) is a widely used method that emerged in Japan, Akao (1990). QFD introduces the customer needs and requirements early and in many ways govern the product development process.

The transformation of customers' values and requirements into product properties are often performed by a multi-disciplinary QFD-team. In traditional procurement systems, when design and construction is done by different participants, the QFD methodology can create problems. The "cross-functionality" approach often used when conducting a QFD, can be hard to achieve in traditional construction projects where the design, engineering and production planning and execution phases are separated. The QFD methodology can be suited for projects were one part is responsible for both the design and production and the functional requirements for both the product and the production can be defined in an early stage of the project, and not as a parade of trades, Dikmen et al (2004).

The QFD analysis needs the customer values or requirements as input. This is often evaluated in market surveys where different market segments are investigated using statistics and customer questionnaires, Eldin et al (2003).

4. CASE STUDY

4.1 Company

The investigated company is one of Sweden's leading modular family house manufacturers. Since the start over 50 years ago, approximately 43 000 houses have been built. The company delivers turnkey houses and takes total responsibility for the delivery. Sales, design, manufacturing and on-site assembly are performed by inhouse staff. The company exports houses to Denmark, Germany and Japan. Customers include both private individuals and business to business clients. In 2008, the turnover was € 91 Million and in total the company employs a workforce of approximately 320 people. Houses are manufactured in both contemporary and classic designs and the targeted end customer group is predominantly middle- and upper middle class.

4.2 The product family investigated

The investigated product family is an affordable house model offered by the manufacturer, it contains five models all based on the same construction principles. The design is classic/contemporary with a relatively high standard regarding kitchen appliances, surface materials etc. All models are detached houses spanning between 100-180 square meters of living space, manufactured in the production facilities of the manufacturer and delivered and assembled as turn-key house to the customer.

The product family is offered at a competitive price with limited possibilities for customization. The product family is designed by the company associated architect with the intention of creating solutions that do not need to be modified. The strategy is to streamline house production and minimize one-of-a-kind operations. The customization options are mainly selection of façade, kitchen appliances and wall coverings.

4.3 Product documentation system

CAD is the predominant product description system for the investigated product family. AutoCAD is used for design and customization of all house models in the company. The AutoCAD system is used for the architectural, structural and HVAC design. Production design rules have been implemented in AutoCAD using VBA interface (Visual Basic Application). The production design rules with associated parameters are stored in an MS Access database. The company is also using an in-house developed MRP/CRM-system (Material Resource Planning/Customer Relation Management) that keeps track of stock and orders along with customer data. Product related information is consequently kept in two systems, the AutoCAD and MRP system, dependent where the information is created, i.e. design information is kept in the CAD system and information related to purchase, stock and customer is kept in the MRP/CRM system.

As a complement to the information in the CAD system, written manuals exist that contain information about rules and limitations of the building system. There is also a manual describing the design rules of the building system to an external audience of architects, structural engineers and sales agents. It covers the main aspects such as, facade heights, floor plan, openings, roof and floor structure, etc. Other product related information is mostly distributed within the organization through documents and drawings.

4.3 Current process

The sales department is often asked to adapt the offered product to fit customer's individual needs. These changes are often not possible to fulfill without violating the rules of the building system. Although the managements' intention on a relatively restricted customization policy, changes of the original concept is often introduced by the sales department to satisfy the customer. Consequently, these adaptations cause problems both in engineering and production when ad-hoc solutions need to be applied to specific customers. Also, the implications, i.e. additional costs for adaption of the product by the engineering and production units, are hard to evaluate. Furthermore, these ad-hoc solutions are often not reused in other projects since the specific solutions are not analyzed in an attempt to modify and incorporate the changes in the product concept.

These findings from interviews with the sales and engineering emphasizes that there are important issues that need to be resolved:

- The product documentation needs to be adapted to the different processes in the company, e.g. in sales, engineering and production views.
- Changes in one view, e.g. sales view, should be easily traceable in the engineering and production views and vice versa.
- Changes of the product concept affecting the production system should be made in a product
 development process from a strategic point of view making the building product more adaptable to
 customers' requirements. Otherwise, the costs of introducing ad-hoc solutions should be part of
 the product offer to the customer.

Next, we will present a conceptual solution of the product documentation issue using different views of a product model of the investigated product family.

4.4 Organizing the product information in product views

Hvam et al (2008) uses a methodology based on the representation of the product in a hierarchical structure based on Unified Model Language (UML). These representations or *product views* of the product model are used to package and present the product information for a targeted set of stakeholders, (knowledge domain). IKEA is an example of a company working with different product views. IKEA's kitchen configuration program makes it possible to design and get a price of a custom made kitchen directly on their website, IKEA (2009). Information essential for the customer such as cabin doors and colors etc, are presented in the customer view of the product. Then, in the production view of the customized kitchen the types of colors and cabin doors is described with article numbers, color codes and other related information used in the production of the custom made kitchen. This information is added in the manufacturers CAD programs different from the one used on the website. The use of process adapted product views of the same product is common in the manufacturing industry and to some extent also in the AEC (Architectural, Engineering and Construction) industry. However, the different views in the AEC industry is mostly connected to the architectural, HVAC and structural disciplines using drawings and documents making the integration and coordination between different disciplines a tedious manual task prone to errors, Jongeling and Olofsson (2007).

The product views with their related product structures also constitute the point of departure for organizing, storing and communicating product information both internally and externally, which would facilitate the information sharing in the customization process, Hvam et al (2008), Johnson et al (2007).

The following product views were defined in the case study:

- The Customer view represents an instance of the product model as it seen by end customers and sales agents which represent the company. This view represents the features of the product family requested by customers.
- The *Engineering view* represents the various customized alternatives of the product model from an engineering point of view. Here the different systems such as structural, installation, etc. are shown important for the technical realization of the product features requested by the customers.
- The *Production view* describes the different building parts to be manufactured at the production facility. It contains information relevant for the supply chain and the factory production units.

 The Assembly view describes how the product will be assembled on site. Assembly instructions, the order of delivery and assembly of prefabricated elements, schedules etc are example of information relevant in the assembly view.

Compared to Hvam et al (2008), the assembly view has been added to the product views in the case study.

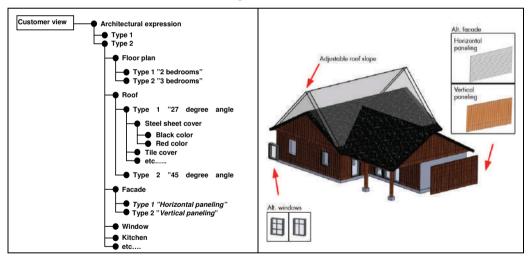
4.4.1 Customers view

Fig. 1 a) - d) show the customers view of the product family. The customization options consist of selecting between two types (henceforth referred to as type 1 and 2) of models within the product family. Within e.g. the type 1 concept the customer can for example choose from altering the floor plan to consist of either two or three bedrooms, an adjustable roof slope with two optional colors (red, black), two types of façade paneling and two types of windows. Table 1 summarizes the flexibility types of the customer views of the product family concept according to Leckner & Lacher (2003).

Table 1: Flexibility of the product family in the customer view

Alternative	Flexibility
Type 1 or Type 2	Alternative component model
Type 2 – Floor plans: 2 or 3 bedrooms	Optional component model
Type 2 – Roof: 27° or 45°	Attribute enumerated set model
Type 2 – Roof: red or black color	Attribute enumerated set model
Type 2 – Façade: vertical or horizontal paneling	Attribute enumerated set model
Type 2– Façade: Window type 1 or 2	Attribute enumerated set model

The alternative floor plan with three bedrooms is not a true add-on configuration (optional component model) since the alternative will affect the size of the living room.



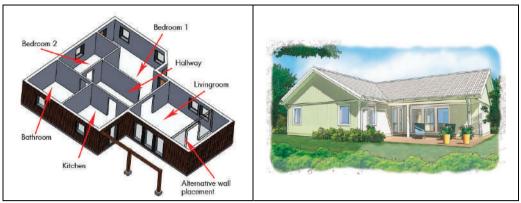


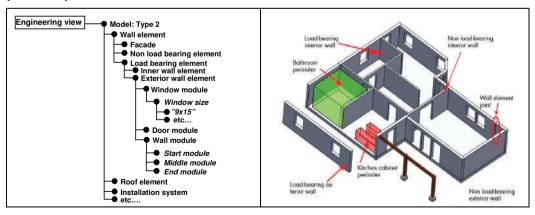
Figure 1: The customers view of the product family Type 2 alternative. Figure 1a) shows the product structure, 1b) the façade, 1c) the interior floor plan and 1d) an example how the configured product is presented for the customer.

The customer product view shows the choices that are important in the context of the sales process. Here the prominent parameters are; architectural expression of the floor plan, and exterior. The details of the structural system, installations etc. are not included since they are not important for the customer. Nevertheless, the engineering and production parameters need to be verified already in the sales stage to avoid the creation of adhoc solutions propagating downstream to the engineering and production stages.

4.4.2 Engineering view

Fig. 2 shows the engineering view ensuring that the customers' choices can be technically realized by the company. This view represents the technical solutions that fulfill the features requested by the customer. The engineering view is meant to be used in the design of new products or new features in a product family considering the constraints given by standards, regulations, production system, etc.

In the engineering view, the structural system of the product family is shown in Fig. 2a). The load bearing and non-load bearing wall blocks including openings for doors and windows are shown to be able to test the structural integrity of the product family model. In Fig. 2b) a space object has been inserted in the bathroom as a carrier of functional and customization requirements to the engineering view, e.g. bathroom requirements on the walls facing the bathroom. Fig. 2c) and 2d) shows how a wall can be decomposed or modularized in units that can be reused in product development. The combination of these engineering modules into the different wall types in the product must abide the rules of the production system, e.g. they must be able to be produced by the production system.



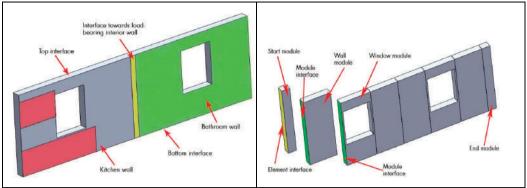
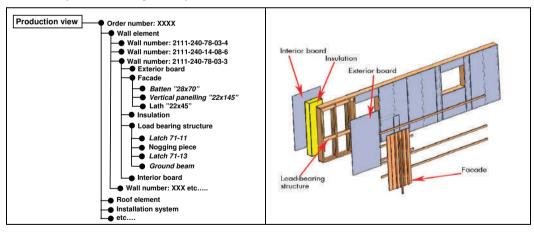


Figure 2: The Engineering view of the product family type 2. Figure 2a) shows the product structure, 2b) the structural view of the interior floor, 2c) an example of a load bearing exterior wall and 2d) its modular composition.

4.4.3 Production view

The production view gives a detailed description of the building parts to facilitate the pre-manufacturing in the factory. It contains information relevant for the supply chain and the production system. The production product structure can also be used to create the bill of materials, BOM, and hence link the production view to MRP (Material Resource Planning) and ERP (Enterprise Resource Planning) systems in the company.

Fig. 3 illustrates the product from the production point of view. Here, the elements to be pre-manufactured are presented with the necessary information for production. Fig. 3b) shows an exploded view of the wall, Fig. 3c) the wall framework while Fig. 3d) contains BOM list and information necessary for manufacturing of the wall assembly. CAD applications tools used in manufacturing industries are often possible to connect to various PDM (Product Data Management) and PLM (Product Lifecycle Management) systems. CAD applications used in the AEC industry often lack this possibility.



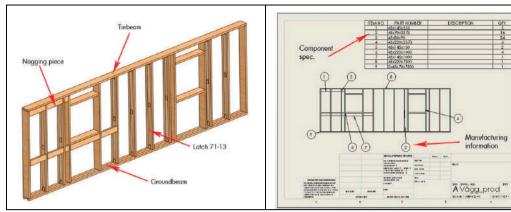
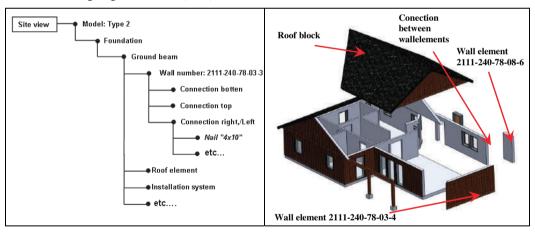


Figure 3: The Production view of a customized order. Figure 3a) shows the product structure, 3b) an exploded view of the highlighted wall element, 3c) the framework of the wall and 3d) its BOM list and manufacturing information.

4.4.4 Site view

Fig. 4 shows the site or assembly view that provides information on how the product will be assembled on site. Information needed in this view is assembly instructions, the order prefabricated elements such as roof blocks and wall elements need to be delivered to the assembly site and schedule. Fig. 4a) shows the assembly product structure, 4b) an exploded view of the product to be assembled, 4c) connection details between assembly components and 4d) a flow line view of the assembly schedule. The assembly drawing focuses on the connection between different elements to be assembled. The proposed scheduling method is flow-line or Line-of-Balance because of its ability to plan and analyze the assembly for work-flow and possibility to combine with 4D visualization, Jongeling and Olofsson (2007).



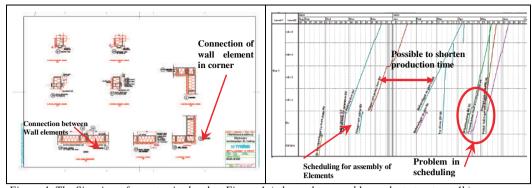


Figure 4: The Site view of a customized order. Figure 4a) shows the assembly product structure, 4b) an exploded view of the assembly structure, 3c) assembly drawing of connections and 4d) the assembly schedule expressed in a flow-line diagram.

Next, we will analyze the product family model, type 2 concept from a customers point of view represented by a recent Swedish customer survey performed on the Swedish housing market.

4.5 Customer Requirements

According to the company the house model are targeted towards families looking for a customized house with relative high standard regarding materials and construction but not with too many other choices, see possible alternatives in Table 1. Actually, the studied case company referred themselves as an engineering company focused more on the demands from the production department than demands from customers. However, if these models are to be successful on the market the offered alternatives must be based on market analysis of the consumer segment.

According to Eldin et al (2003), customers' requirements must be based on market research using surveys and interviews with prospective customers. To exemplify the importance of adapting the product to market trends, the product offers of the product model have been compared with a recent survey of the Swedish housing market regarding demands and wishes, Horsman W. M. (2008). The Internet survey, performed in 2008, received some 5000 answers where some 1600 answer came from people living around the city of Stockholm. The respondents varied in age between 18 to 65 years. The result of the survey was also confirmed with customer demands received by the sales office in Stockholm in interviews with key employees. In Table 2 the top ten demands from the survey and the willingness to pay are compared with the product offers of the product model.

Table 2 Customer top ten demands, Horsman W. M. (2008), compared with the product offers of the product model

Housing	Rank	Willingness to pay	Offer
The housing have central controlled functions that is connected to internet, such as possibility to check the fire stove, turn on alarm, etc.	1	34%	no
It is possible from a central place to control environmental climate systems and light system etc.	2	40%	no
There is a possibility to have built in speakers and media players etc.	3	25%	no
It is easy to rebuild the floor plan for handicap requirements	4	28%	no
The house is easy to access with Wheel chairs and baby carriage	5	28%	yes
Possibility to compensate for climate	6	38%	no
Flexible floor plan with for example movable walls etc.	6	18%	no
The housing is built in a way that lower sound disturbances between bedrooms etc.	8	40%	no
There is a high standard regarding kitchen and bathroom	9	55%	yes

The building is close to culture and activities performed in spare time for example	10	28%	n. A	l
restaurants and theaters etc.				ĺ

Remote control of indoor climate, flexible floor plans, noise reducing walls between rooms, high standard in kitchen, etc, are among the top alternatives which customers have a relatively high willingness to pay for. In a survey performed in Holland "type of kitchen" also ends up as the most important customization alternatives, Hofman et al (2006). These types of investigation provide valuable information on customization options for the house building manufacturers.

5. ANALYSIS

5.1 Organizing the product documentation

Product modeling initiatives have often tried to grasp complex product architectures of entire houses with structures in the same model. This has most certainly not been successful. Less complex information models of the reality (universe of discourse) and better adapted to working processes has probably a better chance of success, Sandberg et al (2008). As illustrated in section 4, the product model was structured in four views, capturing the information needs in the customization, engineering, production and assembly process at the site. The control over the product comes from the ability and the way these views are described and connected, i.e. the transformation of information downstream and upstream the value chain. Fig. 5 illustrates the connection between the different views.

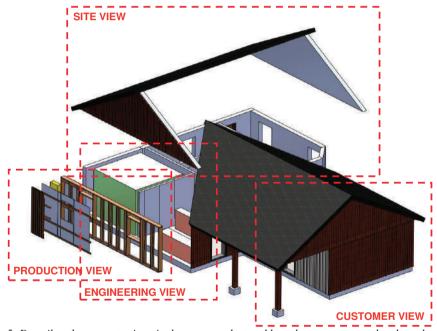


Figure 5: Describes the separate views in the same product and how they are connected and overlay each other

Today, most experiences from earlier projects are seldom documented; they exist only as tacit knowledge in people working at different departments, Sandberg et al (2008). The company knowledge of the product becomes fragmented since it can only be transferred to co-workers in close proximity. This was also evident in the case study company, since informal knowledge had been noted on personal copies of CAD files and product documents. Benefits of integration of product knowledge using product model technology are manifold; less problems with ad-hoc solutions, better and faster product specification process, ability to develop and modularize technical solutions to better match customer requirements, integration of the flow of information between sales, engineering, production and site assembly, etc. Today, there exists a multitude of product modeling technologies, and system that can manage complex products. However, most methods and tools are still limited to support the design, development and production of single products, Claesson et al (2001). The

extent of the product family should be modeled (digitally represented), and IT-systems must be adapted to the manufacturer's product portfolio and economical and organizational abilities. Often only the geometric description of products generated by CAD systems is managed directly, Sudarsan et al (2005).

5.2 Customer requirements versus product offers

Many of the highest ranked customer needs cannot be offered by the product family investigated. The comparison between customer survey and the customization options indicates that there is a mismatch between product offers and requirements in the market segment. This can be one reason for the ad-hoc solutions observed in order to satisfy the customer. Another possible cause is the inability of the company to transfer information of rules and constraints of the building system to the sales organization. Also the company self image as an engineering company might underestimate the importance of adapting the building system to the end customer requirements. The product should be continuously developed to adapt to customers volatile requirements and trends in the market segment. Therefore, experiences from the sales department should always be analyzed and incorporated in development of the building system. New product options should only be implemented as a result of a strategic decision to develop the building system.

5.3 Information flow with product modeling technology

All orders are verified against a checklist, which describes the customization rules (constraints). It contains detailed information of the house to ensure that products can be efficiently manufactured. Although the checklist gives the impression that the company uses a bottom up approach, i.e. let the customer decide then adapt the design to the system. However, the interviews gives the opposite impression that a top-down approach is used – the customer chooses a model which then can be modified according to certain rules. According to sales office, they do not have contact with engineering and production departments before the customer signs the contract. However, to sell the product they need to agree on certain changes of the product, to be able to satisfy the customer. These statements indicates that the link between customer view and the other views (engineering, production and site) are weak. When the customization process violates the rules of the building system, this information is not automatically transferred to the engineering and production view which is a major source of ad-hoc solution in production. Attempts to reduce ad-hoc customization have been to offer fewer options, but this also increases the risk of removing the wrong options from a customer perspective.

It has also been shown that it is much easier for companies to transfer information downstream the value chain than transferring information, rules and constraints upstream, see Fig. 6. Thus, problems related to information transfer should be addressed by creating paths and tools for information exchange upstream the value chain and agree on mutual views of the product. If the information and constraints illustrated in the separate views can be described for all disciplines involved in the process "ad-hoc" solutions can be minimized. The constraints are often too many to manage without the support of integrated information systems such as PDM and ERP systems in the customization of the product.

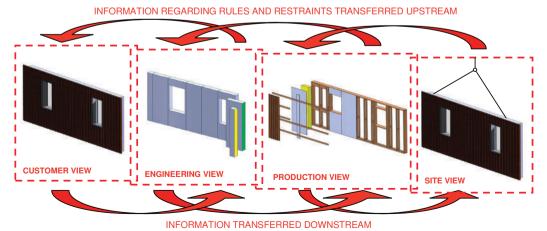


Figure 6: The connection and integration of information between the separate views

6. CONCLUSIONS

Product modeling is a suitable technology to describe the product structure of modular houses. It gives the manufacturers the opportunity to get a view of the entire product range. Creating adapted views makes the product structure less complex to implement. The integration between the different views consists of information transferred downstream from the customers view to the engineering, production and assembly view. The rules and constraints of the building system are transferred upstream from the assembly, production and engineering view to the customers view and hence define the customization limits of the product family. The case study also showed that product development of modular houses must start from customers' requirements. Too little attention of adapting the production system to the volatile customers' expectations increases the risk for ad-hoc solution propagating to manufacturing and assembly on-site with considerable higher cost as a result. Eventually the product will be harder sell. It is also evident that the ICT-tools used to create and manage the different views are view specific, as long as the information and constraints can be transferred between the tools. We believe that successful cooperation and information exchange between these four views is the key to future development and customize-to-order configuration.

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REFERENCES

Akao Y. (1990). *Quality Function Deployment QFD*, Integrating customer requirements into product design, Productivity Press, New York, US.

Bertelsen S. (2005). *Modularization – A Third Approach to Making Construction Lean?*, Proceedings of the 13th Annual Conference of the International Group for Lean Construction, Sydney, Australia.

Björk B-C. (1995). Requirements and information structures for building product data models, Doctoral dissertation, Technical Research Centre of Finland (VTT), Espoo, Finland.

Brege S. (2008). *Presentation during workshop for Lean wood engineering program*, Department of Management and Engineering, Linköping university.

BuildingSmart (2009). www.iai-tech.org, accessed on 20091207.

Claesson A., Johannesson H. and Gedell S. (2001). *Platform Product Development: Product Model a System Structure Composed of Configurable Components*, in proceedings of DETC'01 ASME 2001 Design Engineering Technical Conference and Computers and Information in Engineering Conference, Pittsburgh, PA, September 9-11, 2001.

Dikmen I., Birgonul M. T., Kiziltas S. (2004). Strategic use of quality function deployment (QFD) in the construction industry, Building and environment, Vol. 40, pp. 245-255.

Eldin N. & Hikle V. (2003). Pilot study of Quality Function Deployment in construction projects, Journal of construction engineering and management, pp 314-329

Erixon G. (1998), *Modular Function Deployment – A Method for Product Modularization*, Ph.D. thesis, Dep. of Manufacturing Systems, Royal Institute of Technology, Stockholm.

Hvam L., Mortensen N. H. and Riis J. (2008). Product Customization, Springer-Verlag, Berlin Heidelberg.

Hofman E., Halman J.I.M. and Ion R. A. (2006). *Variation in Housing Design: Identifying Customer Preferences*. Housing Studies, Vol. 21, No. 6, 929–943. Taylor & Francis.

Horsman W. M. (2008) (In Swedish) Botrender 08, En rapport om framtidens boende, Tyréns AB.

IKEA (2009). www.ikea.se accessed on 20091207.

Johnsson H., Persson S., Malmgren L., Tarandi V., Bremme J. (2006). IT-stöd för industriellt byggande i trä (in Swedish) Technical report 2006:19, Div. of Structural Engineering, Luleå University of Technology.

Johnsson H., Malmgren L. and Persson S. (2007). *ICT support for industrial production of houses – the Swedish case*, CIB W78, Maribor, June 2007.

Jongeling R. and Olofsson T. (2007). A method for planning of work-flow by combined use of location-based scheduling and 4D CAD, Automation in construction, vol. 16, Issue 2, 189-198.

Jørgensen K. A. (2001). *Product configuration- Concepts and methodology*, Proceedings of the forth SMESME International conference, Aalborg, May 2001.

Leckner T., Lacher M. (2003). Simplifying configuration through customer oriented product models, International conference on engineering design, ICED 03 Stockholm, August 2003

Lee G., Sacks R. and Eastman C. (2007). *Product data modeling using GTPPM – A case study*, Automation in Construction, Vol. 16. No. 3, 392-407.

Nasereddin M., Mullens M.A. and Cope D. (2007). Automated simulator development: A strategy for modeling modular housing production. Automation in Construction, Vol. 16, pp. 212-223.

Persson S., Malmgren L., Johnsson H., (2009). *Information management in industrial housing design and manufacturing*, ITcon vol 14, pg. 110-122.

Sandberg M., Johnsson H., Larsson T. (2008). *Knowledge-based engineering in construction: the prefabricated timber housing case*, ITcon Vol. 13, pp. 408-420

Schenck D. and Wilson P. (1994). *Information Modeling: The EXPRESS Way*, Oxford University Press, New York US.

Sudarsan R., Fenves S.J., Sriram R.D., Wang F. (2005). A product information modeling framework for product lifecycle management, Computer-Aided Design 37(2005) p.1399-1411, Elsevier.

Vennstra V, S Hallman J. I. M. and Voordijk J.T. (2006). A Methodology for Developing Product Platforms in the Specific Setting of the House Building Industry, Research in engineering design, 17 (3), pp157-173, Springer-Verlag London Limited.

Yang D., Dong M. and Miao R. (2008) Development of a product configuration system with an ontology-based approach, Computer-Aided Design 40(2008) p.863-878, Elsevier.



PRODUCT DEVELOPMENT THROUGH LEAN DESIGN AND MODULARIZATION PRINCIPLES

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ABSTRACT

Customers' demands regarding quality and cost efficiency caused the Swedish construction industry to increase its levels of prefabrication. However, the main focus has been on the structural design and production in the development of these new building systems, and very little attention has been devoted to customer needs and requirements. This has created a situation where ad hoc solutions have been introduced to adapt the building system to match the project requirements, causing problems in the production process with waste and quality problems as a result.

Therefore, a development project was initiated with the goal to design a new building system for multi-story timber housing that could match the client needs and requirements. This paper describes how this development process was pursued using lean design methods and modularization principles.

A multi-skilled development team worked for over 6 months in developing a technical and a process platform for a flexible building system. The study shows that it is evident that modularization principles can be used in order to develop flexible building systems that better can match the requirements from an individual project. From a set of rules, the architect can configure and design a unique building which enables the manufacturability of the building system and ensures a smooth assembly process of the prefabricated modules on the construction site.

KEY WORDS

Lean design, modularization, configuration, prefabrication, product development.

INTRODUCTION

An ambitious housing programme implemented between 1965 and 1974 by the Swedish government with the goal of producing 1 million affordable dwellings, resulted in a dramatic increase in the use of prefabricated components. The impact on productivity and quality was tremendous (Bertelsen 2005). The Swedish single housing industry also introduced a number of new prefabricated building systems based on mass production principles from the manufacturing industry. The demand on production volume and low cost resulted in technical solutions with low flexibility and no possibility of customization, (Höök 2005). Since then, customer demands have increased dramatically and according to Veenstra et al (2006), "Customers are demanding products that match their individual preferences and tastes". Thus, initially well designed standardized solutions have deteriorated when ad-hoc solutions have

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been introduced to adapt the building system to match the customer demands and project requirements. The ad-hoc solutions cause problems in the production system with waste and quality issues as a result, (Malmgren and Jensen, 2009). The demand for customization has made the manufacturing industry develop new methods to adapt their mass produced products better to the needs of the individual customer (Erixon 1998, Hvam et al, 2008). Can the same methods be used to develop more flexible building systems?

In contrast to the manufacturing industry, the building industry is project-oriented. The focus on an individual and unique project could be a reason for the fragmentation in the construction process with little continuity and low productivity as a result. A more product oriented approach, separating the product development process from the adaption to the specific project, using methods developed in the manufacturing industry can make the construction industry more efficient (Lessing 2006). However, in the development of a flexible building system, it is essential to identify and describe the needs and requirements coming from the different stakeholders in the value chain of the building process. The stakeholders' views and requirements need to be incorporated and resolved in the project configuration of the building system (Hyam et al 2008).

OBJECTIVES, AIM AND METHOD

The aim of this research, of which this study is one part, is to develop a configurable multi story timber housing building system that can be adapted to a specific customer demands and produced efficiently with a high degree of prefabrication. The purpose of the study is to investigate how different disciplines can be supported using Lean design methods like Quality Function Deployment, (QFD) and modularization principles adapted from the manufacturing industry in the development phase of a building system. In the case study conducted, the main authors from Tyréns AB worked as a structural design engineer and a process engineer with the development of the building system. They also were a part of the development team that introduced the concepts of modularization and Lean design.

THEORY

LEAN PRINCIPLES AND BUILDING SYSTEMS

Lean principles have been applied on a wide range of processes with the overall aim to minimize waste and maximize value for the client. Toyota has successively applied Lean principles in the development and production process of new car models, (Womack and Jones, 1990). Recent research illustrates that Lean principles can be used in the design phase of construction projects in order to maximize, client and end user-value in construction projects (Koskela et al 1997).

By standardizing both the building parts and the production processes, Lean principles can reduce variation, and minimize waste (Morgan and Liker 2006). The prefabrication and production of construction components under controlled conditions in a factory plant can reduce complexity and variation in the construction process (Höök and Stehn 2005). Björnfot and Stehn (2008) also argue that the standardization of the building components will in the long run provide the benefits in the building process. This argument emphasizes that a building system not only consists of a technical platform, but also a platform of processes that delivers the final product to

customers. Lessing (2005) defines a building system consisting of a development phase and a configuration phase, see figure 1. The development phase includes the development of a technical and process platform. The platforms will then be used in the configuration phase adapting the building system in the specific construction project. The generic platforms (technical and process) can be continuously improved (Kaizen) through lessons learned in the configuration and production of the individual projects. The feedback will provide information that can be used to enhance the flexibility of building system and avoid ad-hoc solutions to solve the problems caused by adaption to customer demands (Womack and Jones 1990).

Methods like Quality Function Deployment (QFD) can be used to identify stakeholders' needs and requirements in the development phase. The results from the QFD are then transformed into product characteristics which can be used to develop the building system, (Womack and Jones 1996). The process platform also includes methods and tools for configuration of the building system for the individual project. Visual planning and control is an important tool where responsibilities, risks, deadlines and status for specific activities are made clear for all stakeholders (Morgan and Liker 2006).

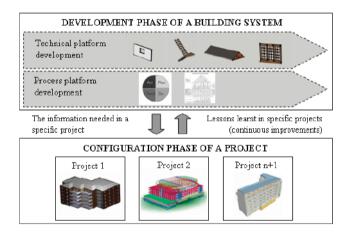


Figure 1: Industrialized housing process (adapted from Lessing, 2006)

MODULARIZATION AND CONFIGURATION

Modularization is a strategy for mass customization of products that have been used successfully by the manufacturing industry, (Erixon 1998, Hvam et al 2008, Ulrich and Eppinger 2008). However, it is important to know what generates value for the customer when the product is modularized into standardized parts. One approach is to standardize parts and modules which are invisible or indifferent to the customer. The visible parts and modules should be open for product customization, (Bertelsen 2005). Using modularization, modules can be shared and configured according to customers' needs and requirements. It is also evident that when a system is divided into smaller parts or modules, the complexity of the system reduces. The complexity of the system can be concealed behind "an abstraction and an interface" (Baldwin and

Clark 2000). Two factors of great importance in the modularization of a product are the independence of components and interfaces (Erixon 1998, Vorrdijk 2006, Hvam et al 2008).

Erixon (1998) developed a method called MFD (Modular Function Deployment) that systematically investigates different strategies in the modularisation of a product. In the MFD method the development starts with conducting a OFD of the product and finding the customer needs in a specific market segment. These kinds of market surveys and system analyses, well known to the manufacturing industry, are usually conducted by the architect guiding the client in a construction project (Bertelsen 2005). Modularity in building systems has been implemented in the construction industry such as "Cut to fit" modularity that has the property of parameterization, where the interface of the module is the same but the dimensions can change However, the use of methods that define the reason for choosing the modules are rarely used (Malmgren and Jensen, 2009). According to Jørgensen (2001), the main advantages in modularization are that the end product can vary in shape and functions, but the design and production of components and modules within a product family are the same. The design phase is normally replaced by a configuration phase where the product is customized by selecting an appropriate set of module variants from the product family. Scania production system, a producer of customized trucks, is separated into two parts. The first part consists of the production of components and modules separated from the different configured customized products. The production is based on a forecast from sales offices and can be produced without knowing how the final product will be assembled from the produced components. The second part is the assembly of customized products based on a configuration chosen by a customer (Gerth 2008). Product configuration is described by Hvam et al (2008) as an effective way of structuring products composed by standardized parts, but also a method of presenting products to customers. Additionally, when products are structured in a product model this becomes a company common view of the product range that can be shared by sales, design and production departments. According to Hvam et al (2008) "Two of the central principles of product customization are that product ranges should be developed on the basis of modules, and that configuration systems should be used to support the task involved in the customization of the specific products". To be able to address the different stakeholders and disciplines, the product can be defined in diverse views that describe the relevant information for the specific actor. Adapting the information view of the product for the different actors can resolve clashes and avoid "ad-hoc" solutions, (Hvam et al 2008).

CASE STUDY: THE DEVELOPMENT OF A BUILDING SYSTEM

The wood institute in southern Sweden announced a design competition of development of a multi-story timber building, 4-8 stories high. Tyréns AB, an AEC consulting company, put together a multi-skilled product development team in order to develop the building system. In the following, the development of the product and the process platform are first discussed. Finally, the implementation of the configuration phase is described integrating the different views in the customization process of the individual project.

DEVELOPMENT PROCESS

First, the production and configuration processes are developed. These work as templates used later in the building project in order to allow for continuous improvements. For example, if assembly instructions are available, site personnel can describe the problems with the current templates and suggest improvements to be implemented in the next project.

In the beginning of the development phase of the building system, a multi-skilled team was put together, with the task of developing a robust and flexible system. Architects [A], structural design engineers [SE], clients [C] (future proprietor), construction site managers [SM], site managers in factory [FM], process engineers [PE] were amongst the competencies included in the team. The process engineers were in charge of developing, and later on updating and managing, the technical and process platform developed in the study.

In a second step a Functional Requirement (FR) analysis was performed to identify and systematize the needs and design parameters for the building system. Through the FR, the team identified the main characteristics to be supported by the building system. The FR was performed on several levels to capture different requirements. In Figure 2: The FR analysis is described and the requirements that different competencies, mentioned from step 1 performed on the development of the wall module. These Engineering metrics could then be used to develop different kinds of wall elements, such as stabilization wall elements etc. The same kind of analysis was performed on other types of modules such as roof, slabs etc.

After the initial mapping was finalized the next phase was started. Weekly two-day design meetings took place. These were conducted in order to concurrently design the technical platform. Visual planning techniques and the use of Post It notes, was an important tool to make responsibilities, risks, deadlines and status for activities apparent for all team members. For each meeting the different team members prepared design evaluation sheets which worked as a foundation for evaluating the work done since the last meeting. The design evaluation sheets also provided the team the capability to follow the evolution of a specific module or part; Allowing the team to track design ideas and information flow.

The technical platform is separated from the building project and as soon as the first version of the technical platform is finalized it can be used to configure a unique building. This first version is then set under change management procedures, where updates through working with continuous improvements (kaizen) in each building project can be implemented after a thorough investigation of the consequences of change. Thus, the new version of the building system can be released that gradually will adapt to the selected segment of the market spreading the investments and risks in the development of the building system over several building projects.

TECHNICAL PLATFORM

The technical platform can be described as the core product description system. Constraints for how different modules can be combined are vital information for the development of the configuration system (Hvam et al 2008). The technical platform developed in the case study is based on the same concept as Scania, where standardized modules can be combined in the customization of the individual project, i.e. separating the development of the technical platform from the configuration process.

	Phase 1: Walls	De	sigr	ı Pa	ram	ete	rs/ i	inpu	t													
sciplir	Functional Requirements Architects [A], structural design engineers [SE], clients [C], construction site managers [SM], managers in factory [FM], process engineers [PE]	Degree of importance	Resist shear forces (low medium high)	Fire resistant load bearing walls (90 minutes)	Vertical load bearing (low medium high) forces	Less then 0,31/min draft	More then 300mm thick insulation	Possible to alter length of wall	Acoustic in apartment not less then class B	Separated apartments	Separated finishes from load bearing structure	Separated installations from load bearing structure	No load bearing walls between rooms in apartment	Maintenance cost less then (xx dollar/year)	Optional to place (doors, windows etc)	Possible to have window openings of 2m	No load bearing walls between apartments	Modularized to system	Standardized connections between modules	No elements longer then 8m	Built in a tent	Possible to stack modules beside each other
Α	Flexible to master plan	а		_		_	_	Х	_	0,	-	-	_	_	х	0	0	_	0,	_		Ť
	Possible to choose installation location	O									0	Х										
	Hidden installations	С									0	Х										
	Possible to have large window openings	۵													0	Х						
	Large windows close to balcony	b													Х	Х						
	Flexible to alter floor plan after built	b						(0)			0		X				X					
	Possible to have different floor plans vertically	а								_			0				Х					
	Alternative finishes outside	а									X				0							
	Alternative finishes inside	а						-		_	Х				0							\vdash
	Horizontal stabilizing	а	Х	Х																		
	Vertical load bearing	а		Х	X					_	_						_	_	_	_	_	\vdash
	Fire resistant for buildings up to 8 floors	a		Х		_		-	_	_			_	_		_	_					
	Noise reducing between apartments	b							Х	X							0					
	Climate protecting	b				X	Х			_				_	_		_	_	_	_	_	\vdash
C	Wind resistant Low energy consumption	a b	Н	\vdash		X			\vdash	\vdash	\vdash			\vdash	\vdash	\vdash	\vdash	\vdash	\vdash	\vdash	\vdash	H
	Low energy consumption Cost efficient constructing		\vdash			X	Х		\vdash	\vdash	\vdash			\vdash	\vdash	\vdash	\vdash	x	0	\vdash	\vdash	0
C	Cost efficient living	a b	H	H			X		-	\vdash	-			X	\vdash	-	-	X	0		\vdash	U
	Simple production process	a					X							X				х	x			\vdash
	Same building techniques used earlier in	a b								_				-				X	^			H
	Short onsite assembly time	a	Н	Н						\vdash	\vdash						\vdash	^	x	\vdash	0	H
	No contact with water during site assembly	а								\vdash				\vdash	\vdash				^		x	Н
	Able to be built of site	а								\vdash										x	^	Н
	Easy to deliver on time	b	Н							\vdash	\vdash									_		х
	Delivered with as few lories as possible	С		Н																		X
	Easy to assembly on site	а																	х	0		
	x = Strong Relationship	Ė	_	_			_	_	_	_	_	_	_	_	_	_	_	_	-		_	_
	o = Medium Relationship																					
	(o)= Low Relationship																					

Figure 2: FR Performed on A Wall Element where Different Disciplines Requirements are Illustrated

The building system is based on a design grid of 150 mm to give the production system greater and better use of materials, and reduce the possible solution space. The same technique was used in an early modular building system where Brooks (2005) defines a key part of the technical platform, with the use of a planning grid enabling the plan to change size and shape at any point of the grid. The production system that will produce the developed modules for the multistory timber house building system is an existing factory producing elements used in single housing projects. Therefore in the development of the technical platform, the production constraints were already given and had to be integrated in the design of the new system. Since the production constraints were imposed by the existing production facility, the manufacturing process of sub-assemblies was given. If a new production system facility would have

been developed, solutions like "walls in walls" could have been developed and implemented with shorter lead time as a result. Many of the modules that have been developed have the function of "cut to fit" modularity such as the framing of joists. Another example is the "stabilization wall" that consists of 3 types: Type A, B and C. The only difference between the different types is the shear capacity. The interfaces are the same and the connections between them are dimensioned for the highest load. Thus, in a configured project some walls will be oversized and stronger than they need to be. Here, a better production system can be developed to lower the total production costs (Gerth 2008). However, this will also be a question of the balance between investments in a new production system versus how these costs can be depreciated over time.

THE CONFIGURATION PHASE OF A PROJECT

The product platform (building system) is adapted to the specific project by configuration of modules and components (Lessing 2006). The rules of how modules can be configured needs to be well described, otherwise "ad-hoc" solutions will emerge. According to Hvam et al (2008), different views have different agendas and focus on different properties of the product (building). For example the architects and customers are most likely focused on the use of the facility where space layout, internal and external textures, appliances etc. are concerned. They are less concerned how the products are manufacture or assembled. However, the requirements from the production system and assembly process will put constraints on the architectural design. Therefore the design tools used by the architect in the configuration process of the specific product need to have these constraints given by design engineers, production experts and assembly staff (Hvam et al 2008). In this sense, describing the modules as objects rather then ordinary drawing tools can make the process more manageable. In the configuration of a building system there are four views that need to be considered, see figure 3:

• **Customer view** - Configuration of the project

• Engineering view - Control, verifying the systems constrains

• **Preproduction part view** - Manufacturing drawings, CNC-code generation

Site view - Assembly drawings, scheduling and site-plans

The customer view describes the building system for the customer and shows the building system from a functional point of view. The configuration tool will be implemented in an architectural design tool such as ArchiCad or Revit. In the case study, the customer view is represented by an architect with knowledge of the constraints of the building project. Implementing the configuration tool, in the development project is still in progress.

When the architect has configured the project, the engineering department needs to check that the configured design is according to the system rules and that the design fulfills the requirements, such as wind and snow loads and energy consumption imposed by the customer, local and national regulations and the location of the final building. Especially in the development of new building systems, configurations that have not been tested need to be verified (Gerth 2008). This step will most likely diminish as more configurations are tested and the configuration tool

continues to develop. After the customization of the project is checked and the client is satisfied with the result, the production drawings and output for the manufacturing process is produced. Here the introduction of design tools used in the manufacturing industries is recommended. The manufacturing industry has for many years worked with parameterization and modularization and these tools are more advanced and adapted to support the manufacturing and assembly process. In figure 3, this is described as the preproduction part view and the use of parameterized configurable modules will greatly enhance the information flow. When the modules such as walls and "framing of joists" have been built in a prefabrication factory they need to be assembled at the building site. In order to create an efficient work flow on site the use of Last Planner System (LPS) (Ballard 1994) is recommended. The use of the CAD model made by the architect can be used in describing the Site view. LPS provides a systematic framework for planning and control of the work flow on-site. Using the Lookahead planning together with the seven prerequisites makes tasks ready to be executed efficiently, eliminating waste in the assembly process.

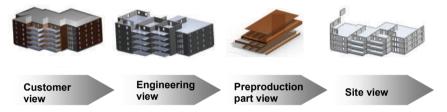


Figure 3: The Configured Product Described in Different Views

DISCUSSION CONCLUSION

A modularized approach in the design and construction of multi dwelling properties offers a solution in designing customized buildings. When technical and process solutions can be repeated over several projects, the time spent in each and every project can to a great extent be reduced. It is also evident that modularization supported by CAD application tools can be the engine that supports the customization process, not only in the configuration of a specific project, but also in the development phase of the building system. If the constraints of a building system can be supported by the different views of interest, "ad-hoc" solutions can be avoided and integrated in the development of the system over time.

The technical platform described in the paper is based on the same modularization principles used in the manufacturing industries. The similarity between the building system and product platforms used in e.g. the Scania's production system is evident. Scania configures their trucks by assembling different kinds of modules to fulfil the customer requirements. These modules can be produced separate from the specific truck but the modules and components used in the truck can be produced on forecast from the sales office. This approach is used in the building system but the decoupling point of the building system (modules and components that the wall consists of, not the whole building process) is earlier in the supply chain. The reason for producing less before the specific project assembly is due to the fact that the production factory is already operating and producing wall elements for the single housing market in Sweden. In the configuration phase of a project, the process consists of a design phase,

defined in the customer view constrained by the rules of the building system. To facilitate the introduction of new building systems on the market, the configuration tools need to be integrated in the design tools used by the architect. The tools have to be able to generate rendered views of the project that the designer is familiar to. The only restriction is that it needs to be object oriented to support definition of the constraints that are put on the design by the building system. The generation of drawings and output to Computer Numeric Control (CNC) machinery in construction applications are generally less developed than mechanical applications. Configuration tools used in the mechanical industry have been working with parameterization longer and also have connection to Product Data Manager (PDM) and Product Lifecycle Manager (PLM) systems that will probably host the building systems of the future. These systems also have version control and change management support.

New building systems for multi-storey dwellings are currently being introduced on the Swedish market by other companies like SKANSKA, PEAB and NCC. This trend will probably continue into other segments such as office buildings. However, a large part will still be traditional construction projects, such as renovation and more advanced building and civil engineering projects since development cost can be large for introducing a new building system.

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REFERENCES

- Baldwin, C. and Clark, K. (2000), "Design Rules" The MIT Press
- Ballard, G. (1994) "The Last Planner". *Northern California Construction Institute* Spring *Conference*. Monterey, California, U.S
- Bertelsen S (2005) "Modularization –A Third Approach to Making Construction Lean?" Proceedings of the 13th Annual Conference of the International Group for Lean Construction, Sydney, Australia.
- Björnfot, A. and Stehn, L. (2008) "A Design Structural Matrix Appraoach Displaying Structural and Assembly Requirements in Conststruction" *Journal of Engineering Design*, 18 (2) 113-124.
- Brookes, A. J. (2005). "Theory & Practice of Modular Coordination" *Proceedings of the 13th Annual Conference of th International group for Lean Construction*, Sydney, Australia.
- Erixon, G. (1998), "Modular Function Deployment A Method for Product Modularization" Ph.D. thesis, Dep. of Manufacturing Systems, Royal Institute of Technology, Stockholm, Sweden.
- Gerth R. (2008), (In Swedish). "En Företagsmodell för Modernt Industriellt Byggande" Licentiat Thesis, Royal Institute of Technology, Stockholm, Sweden.
- Hvam, L. Mortensen, N. H. Riis, J. (2007) "Product customization" Springer-Verlag Berlin And Heidelberg.
- Höök, M. (2005), "Timber Volume Element Prefabrication Production and Market Aspects" Licentiate Thesis, Department of Civil and Environmental Engineering, Division of Structural Engineering Timber Structures, Lule

- Höök, M. and Stehn, L. (2005). "Connecting Lean Construction to Prefabrication Complexity in Swedish Volume Element Housing." Proceedings of the 13th annual conference of the International Group for Lean Construction, Sydney. Australia.
- Jørgensen, K. (2001). Product Configuration Concepts and Methodology. Manufacturing information Systems, Proceedings of the Fourth SME International Conference.
- Koskela L, Ballard G, Tanhuanpää V-P. (1997) "Towards Lean Design Management" Proceedings of the 5th annual conference of the International Group for Lean Construction, Gold Coast. Australia.
- Lessing, J. (2006), "Industrialised House-Building" Licentiate Thesis, Dep. Construction Sciences. Lund Institute of Technology, Sweden.
- Malmgren, L. and Jensen, P. (2008) "Building Product Modelling" Case study of a single house industry company, *intended to be published in Itcon*.
- Morgan, J. M. and Liker, J. K. (2006) "The Toyota Product Development System Integrating People, Process and Technology", Productivity Press.
- Ulrich K. T. And Eppinger S. D. (2008), "Product Design and Development" McGraw-Hill International edition.
- Vennstra, V, S et al (2006) "A Methodology for Developing Product Platforms in the Specific Setting of the House Building Industy", Springer-Verlag London Limited. 157pp
- Voordijk, H et al (2006) "Modularity in Supply Chains: a multi case study in the construction industry" *IJOPM 26,6, 600-618*
- Womack, J.P and Jones D.T (1990), "The Machine That Change The World", Free press, A devision of Simon & Schuster; Inc.
- Womack, J.P and Jones D.T (1996), "LEAN Thinking", Touchstone Books.



Title

Configuration through parameterization of building components

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Abstract

During the last decade many construction companies in Sweden have developed new building systems based on prefabrication strategies to enhance productivity. Current practice and difficulties of introducing these systems early in the design often leads to adhoc solutions creating problems downstream the value chain. In 2008 Tyréns AB, an AEC consulting company in Sweden started to develop a multi-storey timber building system based on modularization principles. Modularization is a strategy for mass customization of products that have been successfully used by the manufacturing industry. The customization process is illustrated using a configurable timber floor slab module. The downstream flow of design information and upstream flow of constraints and rules of the building system are described in three product views; the customer, engineering and production view. Design automation of the configurable floor slab module is implemented in the engineering view in a manufacturing CAD tool. To support the customization process the floor slab module is also implemented in an architectural tool in a LEGO-style customization process. However, a configuration control application that can analyse and map modules within the space boundaries given by the architectural design might be a better approach to get acceptance from the architectural establishment. The demonstrator software shows that today's manufacturing CAD tools opens new possibilities for design automation of modularized building systems in the construction industry.

Keywords

Configuration, Modularization, Parameterization, Building systems, Prefabrication

1. Introduction

New building systems have been introduced by construction companies on the Swedish market during the last decade [1, 2]. A serious obstacle for a successful introduction is the possibility to configure the building according to project requirements considering the

constraints imposed by the building systems [1]. A traditional design-bid-build project often leads to requirements on technical solutions that can be hard to fulfil for an industrialized builder, when system design is already determined. This has lead to ad-hoc customization of the building system that in the worst case are more costly to perform than traditional on-site construction. One measure is to develop a product portfolio, making the customer choose from predefined buildings with small possibilities of customization. This approach has been used by many of the companies producing private homes for the consumer market in Sweden. On the professional market, this approach has not been successful except for specific market segments such as industrial buildings and student housing. Most multi-storey buildings used for rental apartments or condominiums need some form of adaption or customization.

There are two principles of product customization [3]. A product range should be based on *modules* and a *configuration system* should support the task and stakeholders involved in the customization process. In the product development process, methods like design for manufacturing and assembly, [3, 12], are often used to develop components and modules along with the rules and constraints of how they can be combined in the customized product. Therefore it is important that different disciplines are included in the product development team [4]. The rules and constraints of a product platform or a building system need to be included in the development of the customize-to-order configuration system [5].

Fischer and Kunz [6] describe the implementation of Virtual Design and Construction, VDC, in three levels of maturity; (1) Visualization and metrics, (2) Integration and (3) Automation. In the third level, projects use automated methods to perform routine design work based on a building system. The benefits of the automation level are significantly reduced design effort and time-to-market. However, to work with these tools requires that "Project organization normally needs to dramatically change their processes to enable or perform more high-value design", [6]. So far, ICT-tools used in construction industry have often been developed without the possibility of parameterization or direct connections with Computer Numeric Control (CNC). Also, the tools used by the different disciplines in the construction industry cannot easily be integrated [6]. Therefore, much effort has focused on improving the interfaces between discipline specific analysis and design software. A well known model standard for buildings is the BuildingSmart, Industry Foundation Classes (IFC), [8]. However, information transfer between different IFC enabled ICT-tools has shown problems with information loss and distortions [9]. The pragmatic way to solve these problems has been to make direct links between different ICT-tools [10, 19]. According to Zhinling et. al. [11] these connections are mostly developed within a discipline and information exchange across discipline borders are often done using drawings distributed on document servers, FTP-servers or e-mail.

The research aims to investigate how rules and constraints of a building system can be integrated in a configuration process made by architects early in the design process in order to reduce the existence of ad-hoc solutions in the downstream information flow to engineering and production. The process and information exchange are based on

configuration principles and illustrated in a developed demonstrator tool of a configurable timber floor slab.

2. Theory

2.1 Modularization

Modularization is a strategy for mass customization of products that have been used successfully by various industries, [3, 12, 13, 14]. When a complex system is divided into smaller parts or modules, its complexity can be reduced [15]. Two factors are of importance in the modularization of a product, the independence of modules and the module interfaces [3, 12]. The main advantages in modularization are that the end product can vary in shape and functions, but the design and production of components and modules within a product family can be shared [16]. The design is replaced by a configuration process where the product is customized by selecting an appropriate set of module variants from the product family. The development of modularised building systems incorporates the development of modules within the system preserving the interfaces between them [12].

Configurable products can be grouped in three types of modular systems; slot, bus and sectional modularity, [12]:

- Slot modularity is when each module is connected in a certain position by a standard interface. This kind of modularity can be categorized in four sub-types; Component-Sharing, Component swapping, Cut-to fit and Mix modularity. Cut-to-fit modularity has the property of parameterization, where the interface of the module is the same but the dimensions can change. This has been used in many applications in the construction industry. Often the length of a wall is a variable parameter and is thereby stretched according to the rules of the building system.
- Bus modularity is the ability to add extra modules to an existing series of product
 and can be illustrated in the construction industry with the foundation where
 different kinds of wall modules can be placed and where the interface is defined.
- Sectional modularity is when modules has standardized interfaces where the
 modules can be combined in several manners, is used in the construction industry
 when referring to assembly of prefabricated components such as windows, slabs
 and walls.

However, the use of method that defines the reason for modularization is normally not used in the development of building systems in the construction industry [5].

2.2 Configuration

Product configuration as described by Hvam et. al. [3], is an effective way of structuring products composed by standardized parts, but also a method of presenting products to customers. Additionally, products structured in a product model becomes a company common view of the product range that can be shared by sales, design and production

departments. To be able to address the different stakeholders and disciplines, the product can be defined in product views showing relevant information for a specific actor. The product views with their related product structures can be defined according to Hvam et. al. [3] as; Customer, Engineering and Production view. The Customer view represents an instance of the product model as it is seen by end customers and sales agents. The engineering view shows the customized alternatives of the product model from design and analysis point of view, whereas the production view describes the different building parts to be manufactured at the production facility. According to Malmgren et. al. [5], an assembly view also exists describing how the prefabricated sub-assemblies will be assembled at the site in a construction project. If the product design is based on configuration, the role of the engineers will change. Whereas they previously worked out specifications for customized products they now work with development and maintenance of a configuration system [3].

Four different kinds of product specification processes are illustrated in figure 1 where the customer order decupling point is represented with a line dividing the product development of the building system from the specification process of the specific customized building, [3,4]. The first and lowest degree of a defined building system is the well-known *Engineer to order* where the AEC industry design products in regular construction projects such as offices, arenas and factories. The design specification process is mainly based on client requirements, codes and standards. The Modify to order decoupling point is here defined as the use of technical platforms. Typically, construction technical platforms have a generic product structure and constraints in measurements and type of technical solutions, such as standardized floor heights, a selection of approved technical solutions for outer and inner walls, window types etc. The major Swedish construction companies have recently introduced technical platforms on the market, such as "Skanska Xchange", "NCC Bostadsplattform", etc [1]. There is also a number of companies working with standard products in the construction industry where the customer Selects a variant from a certain product portfolio often with minor possibilities of customisation. The Configure to order type of product offers are based on modules and standard parts that can be configured to satisfy customer needs. These type of building systems are relative uncommon. The "NCC Komplett" and the "Bau-how" are examples of more flexible and configurable building systems being launched on the Swedish market during the last decade [1]. However, the NCC Komplett system has now been closed due to poor return on investment.

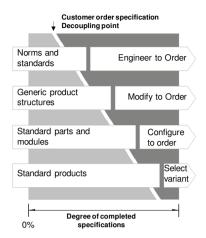


Figure 1: Customer order specification decoupling point for different kind of product offers, adapted from [3, 4]

2.3 Information flow and rule based design

The flow and exchange of information from design to production and between stakeholders is believed to be important in order to improve the construction process. Today, the ICT support used in the construction industry in Sweden is still based on 2D application tools like AutoCAD for drafting, [19]. The vision of storing and sharing information with the use of databases using a common data format like IFC is still not used in practice when jurisdiction in the industry complicates the use of shared models. Also, the implementation of the IFC schema in many commercial applications has shown to be unreliable with information losses and distortions as a result [9]. Therefore, the information exchange between applications relies on propriety data formats, application specific exchange protocols or add-on solutions, [22]. Many of the application specific solutions are based on XML (eXtensible Markup Language) as the transport mechanism for exchange, [11].

Prefabrication strategies and design automation is believed to dramatically increase the productivity in the construction industry, [6]. Traditional design will be transformed into a configuration process supported by knowledge based engineering (KBE) of the final product, [10, 12]. "Software needed for the implementation of the ICT support procedure should have parametric possibilities and preferably object oriented capabilities", [10]. Gross, [7], illustrates this using a constrained based design program, CKB, based on grids and component object design rules. Normally, these kinds of CAD applications can be programmed to automate a rule-based configuration process of the final design. Software like CKB is not intended to be used by the everyday designer or architect. Rather, CKB provides the ability to define a technical system and provide design automation. Nassare et. al. [21] illustrates a constrained based CAD application based on EASYBUILD allowing the designer to automate parts of a design. In the CAD application, ArchiCad, an embedded description language, GDL (Geometry Description Language), can be used to create architectural objects in architectural design. Normally, to develop these kind of applications require knowledge of programming languages like LISP and C++ and access to the CAD application's programming interface, (API).

3. Design automation using modularization and cut-to-fit modularity

3.1 Research approach

In 2008 Tyréns AB, an AEC consulting company in Sweden put together a multi-skilled engineering team in order to develop a multi-storey timber building system free to use for prospective builders in the building sector [19]. A manufacturer in southern Sweden, that normally designs and builds single family timber houses, will manufacture the building parts needed for the assembly of the multi-storey timber building on-site. In the development project constraints and requirements from the production and transportation of building parts were stipulated by the manufacturer. The team decided to develop a modularized system where module variants of building parts such as walls, slabs, etc were designed using slot-modularity. These modules can be configured using cut-to-fit parameterization to fit the architectural design of the building, see figure 2.

Regulations, customer requirements, codes, standards, and production constraints are normally treated in different design stages by separate actors in the building process. Each stage has its own product view and set of design requirements to consider before information is transferred downstream to the next actor in the value chain. This practice often leads to long design iterations and information losses, with conflicts that need to be resolved on the construction site as a result. The different design rules and constraints imposed from different actors and requirements in the value chain must somehow be transparent for all and transferred upstream from production, to engineering and architectural design. This is the role of the configuration system, to support the designers interpretation of design rules and constraints of the building system in the different views. The proposed demonstrator in this paper was later evaluated in a series of semi-structured interviews with the help of students writing there master thesis. During 2-3 hours six experienced architects were interviewed to investigate how they would like to work with the design of the building system in the customer view considering the imposed constraints.

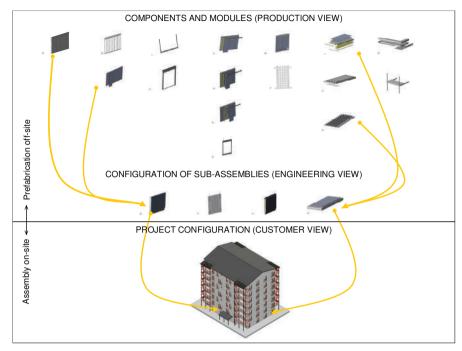


Figure 2: Developed building system for multi-storey timber houses.

Malmgren et. al. [5] defined four product views relevant for industrialized timber building systems; the customer, the engineering, the production and the site assembly view. This paper will concentrate on the three first views and how the information flow, rules and constraints can be integrated downstream and upstream the value chain for a configurable timber floor slab module.

3.2 The timber floor slab module demonstrator

Production view

Figure 3 shows a photograph of the first prototype of the timber floor slab module. People working in the factory need detailed and specific design information to be able to manufacture the different sub-assemblies. Information needed is the specific bill of material, drawings, assembly instructions, article numbers and eventually CNC-operation codes if automated machinery is used in the production of sub-assemblies. Figure 4 summarizes the information flow from engineering to production view.



Figure 3. A prototype of the timber floor slab module sub-assembly

Factory regulations, constraints in production and transportation impose requirements on the engineering design of the timber floor slab module. These constraints are often different from rules imposed in ordinary on-site construction project. Regulations regarding health and safety working in a factory environment at a specific workstation, e.g. height and width of workbenches but also the transportation to site can limit the size of sub-assemblies. In the demonstrator study the floor slab module was limited to:

 $height \le 470 \text{ mm}$ (distance between bench and fixation of nail guns) $width \le min$ (3000 mm, 2400 mm); (workbench, transportation) $length \ge 1500 \text{ mm}, \le 8000 \text{ mm}$ (workbench, transportation)

These constraints needs to be transferred upstream to the engineering design.

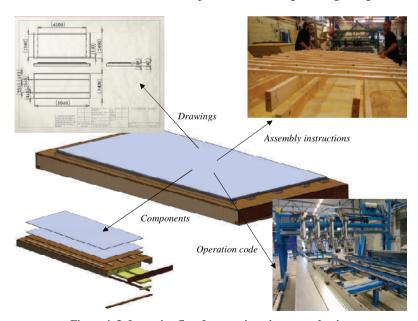


Figure 4: Information flow from engineering to production

Engineering view

Production constraints from production and transportation needs to be integrated with the engineering requirements regarding strength, deflections, fire and acoustics. Also the design should be optimized to give as much freedom as possible for the architectural design to fulfill customer needs and requirements. In many cases flexibility in design must be balanced against demands from engineering and production against the targeted segment of the market. The following limitations of the design of the floor slab were imposed by the requirements from production and engineering:

```
height = 350 \text{ mm} (acoustic, fire and deflection)

width \in (600, 1200, 1800, 2400) \text{ mm} (transportation)

length \in (1500, 1650, ... 5100, 5250) \text{ mm} (workbench, deflection, production)
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ICT-tools used in ordinary construction projects is not adapted to automate the design and manage information exchange with PDM (Product Data Management) system, [17]. Therefore the floor slab is modeled using the mechanical CAD application Solid Works. Solid Works can communicate with a number of PDM systems. Scripting of design rules and constraints was accomplished with the configuration tool Tacton Works Studio making it possible for the designer to program in the Solid Works application environment. Figure 5 shows the engineering configuration in the Tacton Works Engineer dialog and the corresponding design rules and constraints defined in Tacton Works studio.

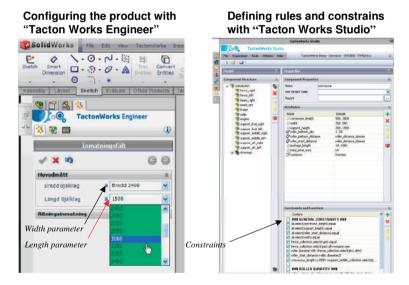


Figure 5: Engineering configuration dialog and function script of the floor slab module

The configuration tool automates the detailed design of the floor slab module and can be used in different projects and easily updated by engineers if design rules or constraints are changed. The script illustrated in figure 5 uses Boolean operators to define the design rules and constraints and describe how the detailed design is altered when the module is configured.

Customer view

In a traditional project the architect produce the architectural solution of spaces and the building the interior and exterior design based on the client's needs and requirements. It is then the job of the engineer to design technical solutions within the spatial boundaries given by the architect. Customisation or customer configuration limits the freedom of the architect. Instead of creating the spatial boundary for the engineer, the architect must now select the most appropriate solution of possible solutions given by the building system. There are at least two approaches to how this could be accomplished. The first way, the "LEGO approach", is to define an object toolbox of modules in the architectural CAD software. The architect can then configure and combine the different module objects into architectural spaces. The other approach is to implement some form of configuration control that can analyse and automatically map modules within the space boundaries given by the architectural design. This second approach is more difficult to implement and requires some form of iterative design to get a perfect match between architectural design and module objects. The first method was used in the study were the floor slab module was implemented as a family in the architectural CAD application Revit Structure, figure 6. Other software, preferably object-oriented facilitating collision control and possibility of some configuration tools, can also be selected [10].

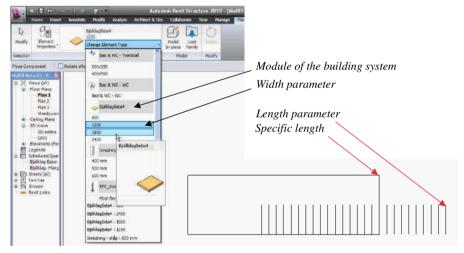


Figure 6: The floor slab module implemented as a family of objects in Revit Structure.

The building system modules can be imported in Revit as a family. The floor slab family consists of four different widths "600, 1200, 1800, 2400", where the length parameter is parametric within the module limits and set with Revits accuracy scale "Course, medium, fine" with a grid of 150 mm. A distance parameter between modules was defined representing the interface when connecting the floor slab to walls. This approach also enables the use of clash detection in the CAD application.

The integration between the customer and engineering view is now a matter of exporting the information of length and width of the different module objects in the architectural

design downstream to engineering. In the study, this was done by implementing an XML export function in Visual basic in the Revit tool, figure 7. The exported XML file was imported by "Load configuration state" in the Tacton Works Engineering tool which automatically generates the information needed to manufacture the floor slabs, illustrated in figure 4.

4. Discussion and conclusions

The result of the demonstration is summarised in figure 8 and table 1. The introduction of building systems and integration of the information flow adds an upstream flow of constraints compared to the traditional way of working in the construction industry. This restricts the solution space but also opens possibilities for design automation. It also reduces the flow of information to a great extent downstream the value chain since much of the information is transformed into formal computer interpretable knowledge that can be shared by the actors in the value chain.

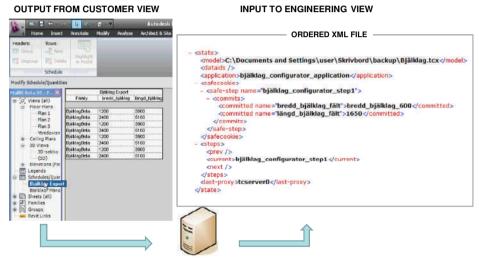


Figure 7. Information flow downstream customer view

FILTERING AND ORDERING

In the demonstration this knowledge was used to implement support tools embedded in the different actors' CAD applications. The definition of views is important to get welldefined interfaces, descriptions and understanding of the product between the different stakeholders involved. This way of information exchange between different disciplines across organisational boundaries also address the opportunity to manage confidential information in contrast to solutions using shared databases and open formats.

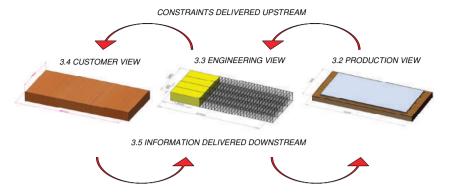


Figure 8: Information flow downstream and upstream the value chain

If only geometrical parameters need to be exchanged between the customer and the engineering view, the IFC-format will most likely be possible to use [9]. This would simplify the downstream information transfer directly from customer to engineering view without the need for developing a specific XML export as described in chapter 3.

Table 1: Downstream and upstream flow of information

Direction	Information downstream /constraints upstream		
From production to engineering view	Transportation		
3 3	Maximum width of timber slabs to 2400 mm		
	Maximum length of element 8800 mm		
	Production		
	Maximum thickness of slabs 470 mm		
	Maximum length 8000 mm, Minimum length 1500 mm		
	Minimum width 600 mm		
From engineering to customer view	Minimum slab length 1500 mm due to factory constrains		
	Maximum slab length 5250 mm due to deflections and fire regulations		
	Slab length a multiple of 150 mm due to system constrains		
	Minimum width 600 mm due to factory constrains		
	Maximum width of timber slabs to 2400 mm due to transportation constrains		
	Thickness of slab 440 mm from engineering constrains		
From customer to engineering view	Module ID and width and length of the module		
From engineering to production view	Bill of materials		
•	Shop drawings		
	CNC files regarding nails, their placement, nail gun pressure and placement of beams		

The development of building systems together with design automation changes the roles of architects and engineers in the construction industry. Design of configuration tools will probably be one task for building engineers in the future. However, most engineering and architectural CAD software used in construction today lack user friendly applications for

the development of configuration tools. Today, this is possible only through the CAD applications' API.

Also, architects have expressed a strong desire to participate in the development of building systems [20]. Otherwise, the introduction and use of such systems can be opposed by the architectural discipline. Architects are an important category and can contribute with knowledge of customers´ needs and end-user behavior especially in the development of building systems. Regarding the use of modular objects in the customisation process architects feel that the configuration system illustrated in this article would restrain the architectural design too much. One of the interviewed architect also meant that the idea was good, but he wanted the freedom to override the configuration system. However, this would most probably lead to ad-hoc customization causing problems downstream the value chain. Changes need to be controlled and only be allowed if new features are implemented in the building system, e.g. the release of a new version [23].

The demonstrator shows that CAD tools used in the manufacturing industry opens new possibilities for design automation of building systems in the construction industry. However, the doubts expressed in the interviews, [20], also implies that architects should be part of the development process of new building systems to ensure that enough flexibility is implemented in order not to restrain the architectural freedom too much in the configuration phase. Also, instead of giving the architect a kind of LEGO tool, a configuration control application that can analyse and map modules within the space boundaries given by the architectural design might be a more appropriate approach to get acceptance from the architectural establishment. If the complexity of the system can be concealed behind "an abstraction and an interface" the abstraction hides the complexity of the element; the interface indicates how the element interacts with the larger system [15]. The customer view is only a functional representation of the technical solution that is defined by the module width and length. How the module is engineered is concealed in the engineers configuration tool.

5. Acknowledgement

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References

- [1] A. Andersson, L. Apleberger, M. Molnár, (In Swedish), Erfarenheter och effekter av industriellt byggande i Sverige, Technical report 0905, FOU-Syd, (2010)
- [2] R. Gerth, (In Swedish), En företagsmodell för modernt industriellt byggande, Licentiate Thesis, KTH, Sweden, (2008)

- [3] L. Hvam, N. H. Mortensen, J. Riis, Product customization, Springer-Verlag Berlin and Heidelberg, (2007)
- [4] G. Winch, Models of manufacturing and the construction process: Genesis of engineering construction, Building Research and Information, 31(2), 1077-118, (2003)
- [5] L. Malmgren, P. Jensen, T. Olofsson, Product modelling of configurable building systems- A case study, To be published, IT-con, (2010)
- [6] J. Kunz and M. Fischer, Virtual Design and Construction: Themes, Case Studies and Implementation, CIFE Working Paper #097, Version 10, Stanford University, October, (2009)
- [7] M. D. Gross, Why can't CAD be more like Lego? CKB, a program for building construction kits, Automation in Construction 5, pg. 285–300, (1996)
- [8] BuildingSmart, [online] Available at: <URL: http://www.iai-tech.org>, [Accessed february 20, 2010]
- [9] T. Pazlar and Z. Turk, Interoperability in practice: Geometric data exchange using IFC standard, ITcon vol 13, pg. 362-380, (2008)
- [10] M. Sandberg, H Johnsson, T. Larsson, Knowledge-based engineering in construction: the prefabricated timber housing case, ITcon vol 13, pg. 408-420, (2008)
- [11] M. Zhinling, L. Heng, Q.P. Shen, J. Yang, Using XML to support information exchange in construction projects, Automation in Construction 13, pg. 629–637, (2004)
- [12] G. Erixon, Modular Function Deployment A Method for Product Modularization, Doctoral Thesis, Dep. of Manufacturing Systems, Royal Institute of Technology, Sweden, (1998)
- [13] K. T. Ulrich, and S. D. Eppinger, Product Design and Development, McGraw-Hill, International edition, (2008)
- [14] M. Lennartsson, Modularity in Industrialised Timber Housing, A Lean Approach to Develop Building Service Systems, Licentiate thesis, Department of Civil and Environmental Engineering, Division of Structural Engineering, Luleå University of Technology, (2009)
- [15] C. Baldwin, and K. Clark, Design Rules, The MIT Press, (2000)

- [16] K. Jørgensen, Product Configuration Concepts and Methodology, Manufacturing information Systems Proceedings of the Fourth SME International Conference, (2001).
- [17] T. Olofsson, E. Cassel, L. Stehn, S. Ruuth, J-O. Edgar, S. Lindbäck, (In Swedish), Produktmodeller i ett flexibelt industriellt byggande, Technical report, LTU-TR-0406-SE, (2004)
- [18] S. Persson, L. Malmgren, H. Johnsson, Information management in industrial housing design and manufacturing, ITcon vol 14, pg. 110-122, (2009)
- [19] P. Jensen, E. Hamon, T. Olofsson, Product development through LEAN design and modularization principles, Proceedings of the 17th Annual Conference of the International Group for Lean Construction, Taiwan, pg. 487-496, (2009)
- [20] P. Sundström (In Swedish), Utvärdering av ett byggsystem: Synpunkter från arkitekter, M.Sc. Thesis, Division of Structural Engineering, Royal Institute of technology, (2010)
- [21] K. Nassar, W. Thabet, Y. Beliveau, Building assembly detailing using constraint-based modeling, Automation in Construction 12, pg. 365–379, (2003)
- [22] T. Racz, and T. Olofsson, Interoperability challenges of an engineering software provider, Proceedings of the 26th International Conference on IT in Construction and 1st International Conference on Managing Construction for Tomorrow, Istanbul, Turkey, pg. 275-285, (2009)
- [23] J. Lessing, Industrialised House-Building, licentiate thesis, dep. Construction sciences. Lund Institute of Technology, Sweden. (2006)