DOCTORAL THESIS

Platforms in Industrialised House-Building

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LULEÅ
UNIVERSITY
OF TECHNOLOGY

Platforms in Industrialised House-Building

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Timber Structures

Printed by Universitetstryckeriet, Luleå 2013

ISSN: 1402-1544
ISBN 978-91-7439-758-1 (print)
ISBN 978-91-7439-759-8 (pdf)

Luleå 2013

www.ltu.se

ACKNOWLEDGEMENTS

My journey has been a combination of scientific work at the university, teaching in computer labs and out at two companies in order to see, find and analyse the problems that house-building designers experience in their day-to-day work. This has given me a good understanding of how to combine practical and theoretical perspectives in research but, most of all, has supported my conviction that research really does have an impact on people's lives. It is a journey where I have developed skills that I never thought possible to develop. I have also seen the beginnings of progress in companies that could change the house-building industry to meet the future demands for prices that young people can afford both in money terms and climatic impact. This would not have been possible without Stefan Lindbäck, who opened the door for me and allowed me to see how an industrialised company, Lindbäcks, carry out design. It was here that, in particular, Börje, Roland and Peter spared me their time to help me study their design work using Lindbäcks' platform. Dan Engström supported me, both with my theoretical and practical disorientations as the anchor at NCC. Anders shared with me his great experience of house-building design development at NCC; also, all those involved at NCC Teknik in Gothenburg are a part of this work. In a research group like the competence centre of Lean Wood Engineering (LWE), research fields overlap and similar areas are studied, which have given me the kind of support that comes from good cooperation. Thank you to Thomas Olofsson for your sharp and efficient skills in applying research to the reality; to Lars Stehn, for your ability to inspire and lead a group by being yourself and to my colleagues in the timber structure team who have shown that research can be efficient but also fun. But mostly, thank you to my supervisor, Helena Johnsson: together with you, it has been a journey full of inspiring conversations, professional criticism of my ideas, always challenging me to develop my work.

Many people have been of great help in my research, but above all I salute my four beloved girls Anna, Alice, Elin and Svea.
I could not have a better team!

Luleå, October 2013.

ABSTRACT

Demands for shorter lead times, customized buildings and high quality deliveries drive house-building firms to systematise work in their supply chains. A practice of reusing processes and technical solutions leads to the formation of platforms in industrialised house-building. Product platforms originate from industries employing a make-to-order strategy, where platforms are used to achieve efficient design and product development work. The house-building design phase, integrated in an engineer-to-order supply chain, has been identified as crucial for achieving an efficient production. In the design phase, design work combines platform predefinitions with project requirements. The aim of this thesis is to describe how house-building platforms are systematised, as well as propose a framework for the use and development of platforms over time.

To expand the knowledge development and use of platforms in house-building design, case studies were conducted that collected data from interviews and observations as well as using archival data at two different companies. One was a Swedish industrialised house-building company, with many levels of platform predefinitions that use off-site production; the other was a Swedish company using several platforms employing industrialised methods for on-site production. The design work of over sixty building projects has been studied through following project managers, engineers and platform developers in their day-to-day work. The use in projects of predefinitions of functional requirements, components, processes and relationships has been compared and contrasted using platform and engineering design theories.

The result of this research shows that, in an engineer-to-order production strategy, creative and systematic designs are combined. This combination is needed to create product uniqueness and thus it is important to understand and maintain the balance between commonality and distinctiveness within the platforms used in house-building projects. Continuously changing demands in construction hinder a fully predefined platform. Long cycle times in house-building demand a continuous flow of knowledge between platform and day-to-day work in projects. Hence, platform versions and product variants often become non-functional in an engineer-to-order supply chain, so methods to support the knowledge flow become necessary. The research findings show that design work, integrated into the supply chain of house-building, is a source of experience feedback for platform development.

The conclusion is that a movement towards mass customization in house-building is possible using the product platform concept, if the platform is applied to projects using support methods with experience being continuously fed back to the platform from house-building projects. However, there is a risk that use of predefinition in platforms is made without considering the consequences. The reuse of predefined processes could limit innovation capability, increase the risk for imitation and organisational inertia. Too great a restriction of components in the house-building platform could limit the product offer and narrow the market segment. The study also shows that predefinitions might lead to an unbalanced focus on buildability instead of client satisfaction.

SAMMANFATTNING

Krav på kortare ledtider, kundanpassat byggande och hög kvalitet på leveranser tvingar byggföretagen att systematisera arbetet i sina produktionsled. Genom att återanvända processer och tekniska lösningar kan det dagliga arbetet utvecklas inom plattformar för industriellt bostadsbyggande. Produktplattformar med syfte att stödja effektiv design och produktutveckling baseras på strategier för tillverka-mot-order produktion. Projekteringsfasen, som en integrerad del av bostadsbyggandets produktionskedja, har identifierats som avgörande för att erhålla en effektiv produktion. I projekteringsfasen kombineras fördefinitioner från plattformen med projektets krav. Syftet med denna avhandling är att beskriva hur bostadsplattformar kan systematiseras, och föreslå ett ramverk för användning och utveckling av plattformar över tid.

För att fördjupa kunskapen om hur plattformar används och utvecklas i bostadsprojektering har fallstudier genomförts genom insamling av data via intervjuer, observationer och arkiv hos två olika företag. Ett svenskt industriellt bostadsbyggande företag med hög grad av fördefinering för prefabricerad produktion. Det andra företaget använder flera plattformar och industrialiserade metoder för platsbyggande produktion. Projekteringsarbete har studerats i över sextio bostadsprojekt genom att följa projektledare, ingenjörer och plattformsutvecklare i deras dagliga arbete. Användandet av fördefinierade funktionskrav, komponenter, processer och relationer har analyserats mot plattforms och designteorier.

Forskningsresultatet visar att kreativt och systematiskt arbete kombineras i en konstruera-mot-order kontext. Kombinationen är nödvändig för produktens unikitet, och därför är balansen mellan repetition och variation viktigt för förståelse om och andvändande av plattformar i husbyggnadsprojekt. Ständigt föränderliga krav inom byggandet hindrar en fullt fördefinierad plattform. Långa cykeltider i bostadsbyggandet ställer krav på ett kontinuerligt flöde av kunskap mellan plattform och det dagliga arbetet inom byggprojekten. Plattformsversioner och produktvarianter blir ofta icke-funktionella i en konstruera-mot-order kontext, metoder behövs därför för att stödja flödet. Forskningsresultaten visar på att projekteringsarbete, integrerat i bostadsbyggandets leveranskedja, är en källa för erfarenhetsåterföring i utveckling av en plattform.

Slutsatserna visar att en förändring mot effektivt kundanpassat bostadsbyggandet är möjlig om plattformar används tillämpade i projekt med stödjande metoder och kontinuerlig erfarenhetsåterföring från byggprojekten till plattformen. Däremot, finns det en risk att plattformar fördefinieras utan att reflektera över konsekvenserna. Användning av fördefinierade processer skulle kunna begränsa innovationsförmågan, öka risken för imitation och skapa förändringsmotstånd inom organisationer. Detaljering av komponenter i en bostadsplattform kan begränsa produktutbudet och minska marknadssegmentet. Studien visar också att fördefinitioner kan leda till obalanserad fokusering på byggbarhet istället för funktionalitet för kunden.

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Paper II:

Jansson, G., Johnsson, H. and Engström, D. (2013) ”Platform use in systems building”. Published in the *Special issue of Industrialised building in Journal of Construction Management and Economics* in May 2013.

Paper III:

Jansson, G., Schade, J. and Olofsson, T. (2013) “Requirements Management for the Design of Energy Efficient Buildings”. Published in *Journal of Information Technology in Construction* in September 2013.

Paper IV:

Jansson, G. ”Continuous development of house-building platform through experience feedback”. Submitted for publication in *Journal of Construction innovation* in October 2013.

Paper V:

Jansson, G., Johnsson, H. and Jensen, P. (2013) “Modularization in a housing platform for mass customization”. *Proceedings of the 29th Annual ARCOM Conference,* September 2-4 Reading, UK

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Appendix 1

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OTHER PUBLICATIONS BY THE AUTHOR

Paper A:

Jansson, G., Johnsson, H. (2008) “Concurrent Engineering in Educational Projects: Case study Svartöberget”. *Proceedings of the 25th Annual CIBW78 International Conference – Improving the Management of Construction projects through IT adoption*, July 15-17 Santiago, Chile.

Paper B:

Jansson, G., Schade, J., Olofsson, T. and Tarandi, V. (2010) “Requirements Transformation in Construction Design”. *Proceedings of the 27th Annual CIBW78 International Conference - Applications of IT in the AEC Industry*, November 16-18 Cairo, Egypt.

Paper C:

Haller, M., Lu, W. and Jansson, G. (2013) “Iteration Based Project Performance Indicator for Management of Building Design Processes”. Submitted for the journal of *Architectural Engineering and Design Management* in August 2013.

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Erikshammar, J., Meiling, J., Jansson, G., and Levander, E. (2010) “Industriellt träbyggande förenar ekonomi och hållbarhet”. Samhällsbyggaren 2, 2010, 32-35.

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Technical report:

Jansson, G. (2009) “Kartläggningen av projekteringsprocessen på Lindbäcks”. Luleå tekniska universitet, ISBN 1402-1536 .

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Holmlund, S., Jansson, G., Lennartsson, M., Simu, K. (2008) “Lean i praktiken: en studie av produktionen på Englundshus AB”. Luleå tekniska universitet.

Licenciate thesis:

Jansson, G. (2010) “Industrialised housing design efficiency”. Luleå University of Technology, ISBN 1402-1757.

1 INTRODUCTION

The introduction outlines the motivation for this thesis followed by the objectives and aims of the research. First, there is a description of the scope of the research into platforms and engineer-to-order supply chains as well as a contextual description of industrialised house-building design.

When designing buildings where engineering and creation of the product is made through a network of decisions and value processing, there are opportunities to increase design output for client value and decrease the cycle times of design processes, by focusing on the use of predefinitions in day-to-day work (Johnsson 2013). House-building design work is integrated into the house-building production supply chain (Winch 2003) and combines creative and systematic activities (Formoso et al. 1998). Pan et al. (2012) claimed that the standardisation of design work is crucial for off-site production using prefabrication, predefinition and industrialised methods. The Swedish house-building sector has seen a strong development of industrialised methods, stemming from the long tradition of industrialised production of single-family houses (Samuelsson 2001). As part of current house-building improvements, predefinition brings lower costs, increased production flow and a higher quality of deliveries (Johnsson 2013, Stehn et al. 2008). Although there are examples where everything is predefined, currently the trend is to industrialise only part of the supply chain. Design work that transforms requirements into design parameters becomes challenging when balancing creative and repetitive work in a partly predefined supply chain. Configuration systems for industrialised house-building have been developed to support design work and drive mass-customization in the design work of house-building production (Hvam et al. 2013, Jensen et al. 2012). Predefined geometry-based systems of components were introduced as “systems building” in the 1950s and 1960s, which in turn were influenced by ideas from factory production (Gann 1996). Consumers had little, if any, choices of design, layout and materials during the realisation of the post-war house-building programmes that ended up being socially unacceptable (Gann 1996, Finnimore 1989). At present, the management of variability in designs for construction is central to the development of underlying systems (Gerth et al. 2013). Industrialised house-building companies are trying to predefine not only buildings, fully or partly, as products but also the related processes and the supply chain (Lessing 2007). The house-building market now provides different choices for its customers (Lu et al. 2011), thus creating a need for building systems able to meet changing demands.

A central aspect for understanding the industrialised house-building process is to categorise the manufacturing process by its level of predefinition. Predefinition is how specified a product already is when the client enters the process i.e. the client order decoupling point, Figure 1.

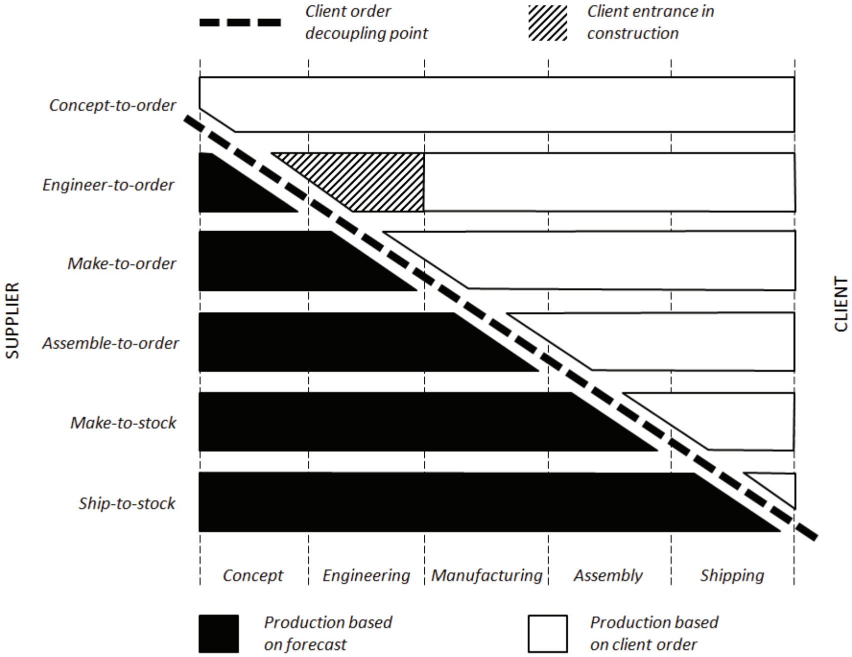

Figure 1. *Production strategies, published in Johnsson* (2013) *from Sackett et al.* (1997).

In an engineer-to-order (ETO) context, the client enters the supply chain somewhere during the engineering phase, as shown in Figure 1, enabling the client to affect the output i.e. to customize the final solution (Hicks et al. 2000). The engineer-to-order supply involves a non-physical stage that includes tendering, engineering and process planning activities, as well as a physical stage that comprises component manufacturing, assembly and installation (Sackett et al. 1997).

Construction is identified as one of the largest engineer-to-order (ETO) sectors (Gosling and Naim 2009).

Operations strategies in construction are mostly expressed in contractual forms. General contracts imply a client responsibility whereas design-build contracts imply a contractor responsibility. However, they both often result in a separated process without overall commitment (Osipova and Eriksson 2012). Design-build contracts enable house-building companies to use industrialised methods with predefinition and prefabrication of their building system, define operations strategies for their supply chain to reach strategic goals, and deliver client value.

Prefabrication, as a part of industrialised house-building, opens up the opportunity to plan for a speed-up of production and achieve better control of the manufacturing process (Höök and Stehn 2008). Design work suffers from inefficiency in deliveries where time, cost and quality are not consistent with the use of resources (Tilley 2005, Magent et al. 2009). Industrialised methods offer systematisation of the design work for house-building companies and integration is therefore critical for the entire production chain.

1.1 Predefinition by platforms

The electronic, car and computer industries manufacture products using a make-to-order (MTO) strategy. These industries have demonstrated the benefits of using predefined rules and systematic standardisation in *product platforms*. Product platforms are described by Meyer and Lehnerd (1997, p. 7) as "a set of common components, modules, or parts from which a stream of derivative products can be efficiently developed and launched". Through product platforms, companies achieve high levels of product variety, a reduced time to market, improved operational efficiency and responsiveness to market needs (Meyer and Utterback 1993, Muffatto 1999). A drawback of using platforms in MTO scenarios has been identified as being the challenge of servicing different product market segments dynamically (Karlsson and Sköld 2007). During platform development in MTO contexts, solutions are separately tested and evaluated so that product development and production development phases can be improved and product functionality tailored for the market (Meyer and Lehnerd 1997).

The construction sector has seen large investments in supporting the industrialisation of construction. Some have been successful, but the large investments required before the production has even started have led to the end for others (Apleberger et al. 2007). Later research has shown the importance of analysing the entire supply chain when developing platform standards so that variability in project demands (client, site) and production (engineering, manufacturing and supplier) parameters are satisfied (Styhre and Gluch 2010, Thuesen and Hvam 2011). A continuous development through experience feedback of platforms has been presented as being beneficial for maintaining the investment (Meiling 2010, Styhre and Gluch 2010, Bresnen et al. 2004).

At the point where variability of client demands meets production parameters, design work becomes the pivot point for success in industrialised house-building. However, the design work supported by product platforms lacks an underlying theoretical understanding. The integration between product, process and the supply chain is central in a platform but a theoretical foundation of how to develop and maintain platforms over time is missing (Meiling 2010, Lu et al. 2011, Lessing 2006). This thesis focuses on the design work in industrialised house-building, identifies the balance between commonality and distinctiveness in it and examines methods to systemise design work without losing the creativeness of design. The product platform concept is considered to be an underlying system. A synthesis of how platforms are used, sustained and developed in industrialised house-building is considered an analogue of a general ETO scenario.

1.2 Thesis aim and scope

The objective of this thesis is to analyse how the platform concept is applicable for ETO scenarios as demonstrated by house-building. To describe and understand the benefits and drawbacks of industrialised house-building platforms, the design work becomes central to the research. Support methods for design work are therefore a valuable source of information, since client demands meet production variables at this interface. It is at this point that tools and theories, developed for the MTO context, are applied in the ETO context. In order to understand how systematised predefinitions support the transformation taking place in design work, studies have been carried out in close collaboration with companies by analysing platform use and development in day-to-day design work.

The aim of this thesis is to describe how house-building platforms are systematised by predefinitions and to propose a framework for the use and development of platforms over time.

Research questions are presented at the end of section 2 with the theoretical framework for house-building platforms as the foundation. Findings (in section 4) answer both research questions by using results from the five appended papers. Proposals (in section 5) give the summarised results from findings. A discussion (in section 6) of findings, research work and results is followed with conclusions (in section 7).

Appended Papers I - V:

Paper I: *Design process organisation at industrial house builders - a case study of two timber housing companies in Sweden*

This work identifies the need for a central storage of standards and gives a problem description of the need for managing project and repetitive activities for unique product solutions. The paper was written by Gustav Jansson, Erik Söderholm and Helena Johnsson and published in Proceedings of the 24th Annual ARCOM Conference, September 1 – 3 2008 Cardiff, UK. Gustav Jansson's contribution was formulating the fundamental ideas together with Erik Söderholm and Helena Johnsson. Gustav Jansson carried out the process mapping and interviews at one of the two case study companies. The writing was divided between all authors.

Paper II: *Platform use in Systems Building*

The paper describes a model of how to use platforms in a project-based production within an ETO supply chain. It also shows how the focus of applied support methods can affect the entire supply chain in house-building. The paper was written by Gustav Jansson, Helena Johnsson and Dan Engström and published in the special issue of Industrialised Building in Journal of Construction Management and Economics in May 2013. Gustav's contribution was formulating the fundamental ideas together with Dan and Helena. Gustav also carried out the study of platform use at the companies and the related interviews. The writing was divided between Helena Johnsson and Gustav Jansson with Gustav as the main writer.

Paper III: *Requirements Management for the Design of Energy Efficient Buildings*

To develop a method of managing requirements in house-building platforms, a systematised structure for energy design, based on axiomatic design, was applied and analysed. The contribution of this work to the thesis is the detailed decomposition of the critical interface between client requirements and supplier solutions. The paper was written by Gustav Jansson, Jutta Schade and Thomas Olofsson and published in the Journal of Information Technology in Construction in September 2013. Gustav Jansson's contribution was to formulate the fundamental ideas together with Jutta Schade and Thomas Olofsson, planning the study and analysing the studied context. The writing was divided between all the authors.

Paper IV: *Continuous development of house-building platforms by experience feedback*

This work contributes to the thesis by examining how experience feedback is useful for the development of house-building platforms over time and how the balance between commonality and distinctiveness is continuously supported by the flow of knowledge in the supply chain. The paper was written by Gustav Jansson and submitted to the Journal of Construction Innovation in October 2013. The writing and formulating of fundamental ideas, planning and execution was carried out by Gustav Jansson.

Paper V: *Modularization of house-building platform for mass customization*

Modularization is a method of breaking down complex products into subsystems that are easier to manage. Modules were identified and the drivers behind their formation were identified. Five modules in the study were not only examined to see how modules could be identified and separated from the supply chain of industrialised house-building but were also used to show how different, important, client drivers affect module identification for production. The paper was written by Gustav Jansson, Helena Johnsson and Patrik Jensen, and was published in the Proceedings of the 29th Annual ARCOM Conference, September 2 – 4 2013 in Reading, UK. Gustav Jansson's contribution was formulating the fundamental ideas together with Patrik Jensen and Helena Johnsson. Gustav Jansson collected the data, analysed and formulated the contributions to the field as well as presenting the work. The writing was divided between Gustav and Helena.

2 THEORETICAL FRAMEWORK

The theoretical framework used in this thesis is illustrated in the context of engineer-to-order, using platform and design process theories. Previous research in the field of house-building is described using platform and engineering design theories.

Design work in an ETO context becomes of central importance if improvements are desired because the client enters the process somewhere in the engineering phase (Hicks et al. 2000). Design work in house-building has the specific purpose of communicating solutions, information sharing and multidisciplinary collaboration but lacks an underlying theoretical understanding. The development of a product platform, together with integrated design and optimising reusability, are the crucial challenges when striving for mass customization (Tseng and Jiao 1998). Using systematic engineering design methods, the platform concept could be applied to the variety and repetitiveness found in a specific construction context (Voordijk et al. 2006). In a shift from the traditional construction design process, with contracts between vertical disciplines in house-building organisations, systematisation of design work becomes an integrator for innovations (Vrijhoef et al. 2009) and has the ability to support the entire supply chain.

2.1 Creative and systematic design processes

If work is seen as a part of producing goods and services for customers, the operation management approach describes design work from a production process perspective (Slack et al. 2007). From an artistic point of view, a design process means creativity, is imaginative and unpredictable, while the engineering view of the design process is more systematic or even automated for production purposes (Slack et al. 2007, Lawson 1997). House-building design processes are a combination of creative and systematic activities (Formoso et al. 1998).

2.1.1 Creative design processes

Creative processes mean developing solutions to unsolved problems. Creative design often involves conflicting, sometimes incompatible, demands (Lawson 1997). The creative design process can be described as a three-part negotiation of activities through analysis, synthesis and evaluation, Figure 2 (Lawson 1997, Hubka and Eder 1982, Malmqvist

2001). Iteration is a simplification of a complex mental process to find solutions to problems.

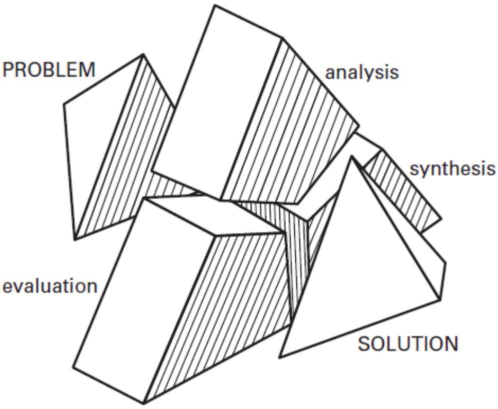

Figure 2. *Design process seen as a negotiation between problem and solution through analysis, synthesis and evaluation* (Lawson 1997).

The negotiation between activities is not directed in a specific order with a start and an end, thus the activities describe an iterative process going through a number of loops. Managing design iterations in the construction design process is managing value for the client through the progress of product definition (Jørgensen and Emmitt 2009). This is not simple to carry out without support in construction, primarily because of the different values held by the supply and demand sides of the supply chain (Emmitt et al. 2004).

2.1.2 From problems to solutions through systematic activities

Much of the literature on engineering design focuses on the structure of stages, activities, tasks and related resources in the design process (Suh 2001, Hubka and Eder 1996, Pahl et al. 1996).

Axiomatic design is a systematic method for the design transformation between the customer, functional, physical and production domains (Suh 2001). The transformations between two domains, such as the functional and physical domains, represent the design task to interpret and translate functional requirements (FRs) into design parameters (DPs), from the most generic and top-level requirement to more detailed requirement levels using zigzag decomposition cycles, (see Paper III). Boundary conditions and system constraints restrict the design space. Decisions made at higher levels act as constraints at lower levels (Suh 2001). From an engineering design perspective, design means transformation of customer attributes (CAs) to functional requirements (FRs), then to design parameters (DPs) and finally to a full description of the proposed technical system with production variables (PVs) and logistic variables (LVs) (Hubka and Eder 1982, Suh 2001, Jiao et al. 2007), Figure 3.

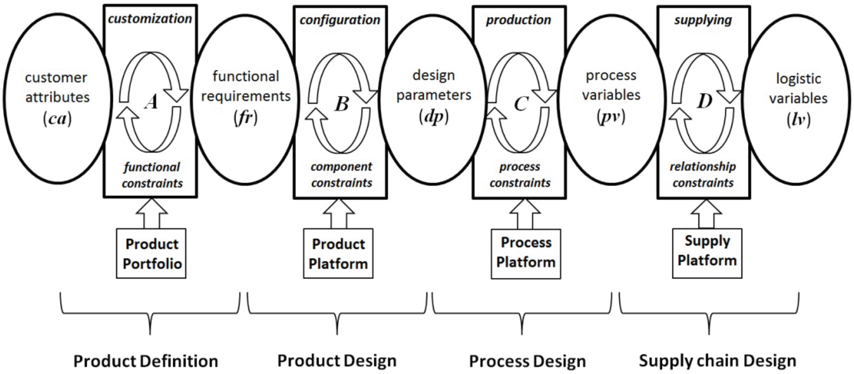

Figure 3. *Product fulfilment using platforms and supply chain domains* (Jiao et al. 2007).

Jiao's (2007) framework involves the mapping of product definition across the five domains using platform as an effective means to achieve economy of scale. In the product design, the downstream flow of knowledge from the demands of customization meets the upstream flow of production and supply knowledge by constraints (arrow loops in Figure 3). In finding downstream flow of knowledge, the design work needs to be managed in parallel, while conventional business processes that manage materials and data tend to be more sequential (Browning et al. 2006). The use of parallel flows enables the reduction of lead times in the design (Prasad 1996), but, to ensure the quality of the solution, iterations are needed which increase the time and cost of the design phase (Le et al. 2012). By using set-based (see Paper III) design and reducing the number of alternative design solutions, stepwise, unnecessary iterations can be avoided throughout the process (Choo et al. 2004).

2.2 Design in an engineer-to-order context

An engineer-to-order supply chain is governed by parameters that are defined in the conceptual phase as demands, requirements and sometimes also solutions, Figure 1. The client order decoupling point

(CODP) in an ETO supply chain is located at the design stage, where each product is different to the last (Gosling and Naim 2009).

> *The customer order decoupling point (CODP) is a stock holding point that separates the part of the supply chain that responds directly to the customer from the part of the supply chain that uses forecast planning. The decoupling point can act as a strategic buffer against the variability in demand and an efficient way of scheduling standardised parts whilst reacting to uncertain orders.*
>
> *(Gosling and Naim 2009, p 743.)*

According to Rudberg and Wikner (2004) and Haug et al. (2009), ETO companies represent pure customization while MTO companies use mass customization concepts such as modularization, adaptive, cosmetic or customized standardisation. The value of increasing predefinition is that it reduces delivery times, allows a more precise calculation of costs, reduces specification costs and reduces the training necessary for new sales personnel. By using a great deal of predefinition in the supply chain, the advantage of short lead times translates into intensive client involvement and faster deliveries (Haug et al. 2009). The challenges of simplifying or trivialising the design work are dealing with the loss of innovative capability, the risk of imitation and potential resistance from within the organisation. Furthermore, the number of clients must be weighed against the cost of platform standardisation projects (ibid). ETO companies that organise their supply chain for mass customization limit product options for their client, potentially limiting their market share.

2.3 Product platforms

Product platforms are frameworks that have been used to manage the separation between production and product development in an MTO context. The benefits of using platforms for design and production are:

- greater ability to tailor products to the needs of different market segments or customers
- reduction of development cost and time
- reduction of manufacturing cost
- reduction of production investment
- reduction of systemic complexity
- lower risk
- improved service

(Robertson and Ulrich 1998)

Robertson and Ulrich (1998) presented a platform planning strategy with design methods that balanced client needs with production costs. Studies of the car, computer, electronic and mobile phone industries describe the product platform as a collection of assets, which are shared by a set of products sorted into components, processes, knowledge and relationships (Meyer and Lehnerd 1997, Robertson and Ulrich 1998, Muffatto and Roveda 2000), Figure 4.

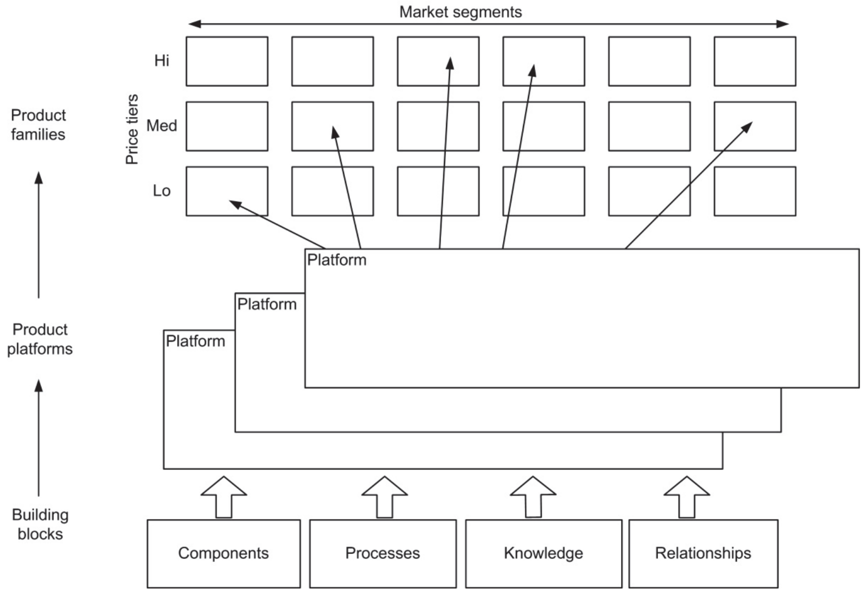

Figure 4. *The Power Tower model of a platform* (Meyer and Lehnerd 1997).

By studying product development in product platforms within the MTO context, Meyer and Lehnerd (1997) presented the Power Tower model in Figure 4, showing the elements of market instantiation by product families, product platforms nurturing several product families and the four basic assets serving as building blocks in the platform. A focal point in Robertson and Ulrich's (1998) platform planning is the balance between *commonality* and *distinctiveness.*

Commonality refers to repetition of functions, physical components or technical solutions (Jiao et al. 2007) and can be used at different levels of a product as well as in and between products, Figure 5.

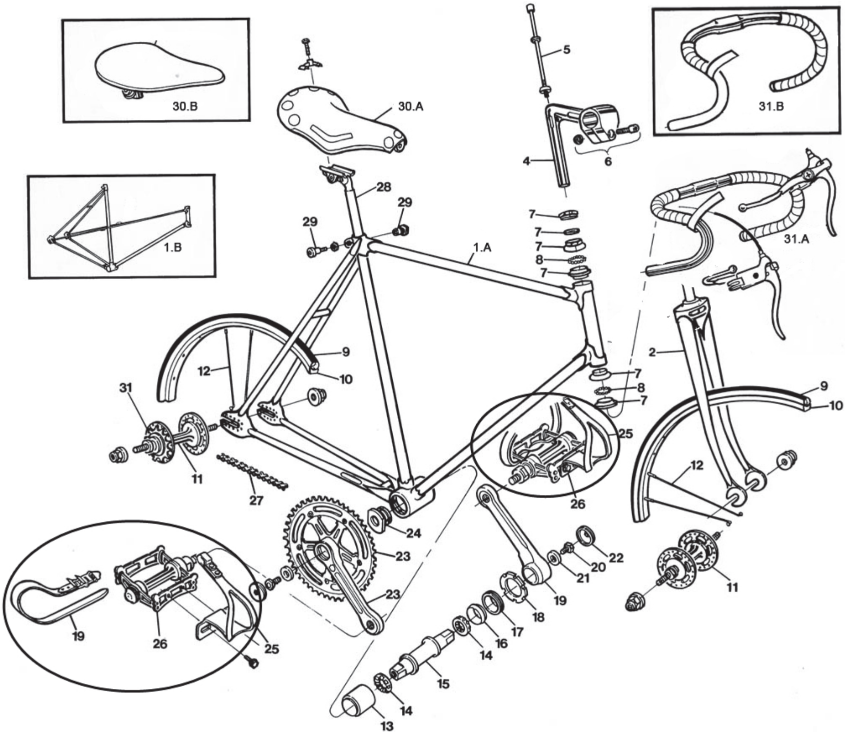

Figure 5. *Example of detail commonality (the same numbers), assembly commonality (ellipses) and distinctiveness (variants in rectangles) from Raleigh Bicycles (1977).*

Commonality is the common base of an MTO platform and the driver for simplicity and cost (component repetitions in Figure 5). Common parts appear in every product model produced within the platform. From a client point of view, the commonality in a platform provides no variety between models. When adding *distinctiveness*, individual product uniqueness is created (variants in Figure 5). Pasche and Sköld (2012) summarised the challenges in platform development:

- balancing commonality and distinctiveness in physical parts
- risk of commonality bias, which can lead to reduced product distinction and over-designed low-end products
- risk of organisational inertia by introducing platforms
- overcoming interdependencies between non-platform and platform parts
- interfaces that are stable throughout the platform life-cycle
- balancing different stakeholder demands

One criticism of product platforms is that there is no long-term perspective on the effects of using them in situations where component commonalities could be disastrous for maintaining a changing market position (Pasche and Sköld 2012). To overcome the challenges of coordination between design and manufacturing and avoiding commonality bias, Robertson and Ulrich (1998) suggested that the organisation quickly processes knowledge about client needs from the demand side. Sensitivity of the organisation to the balance between commonality and distinctiveness can be developed by the involvement of marketing departments (Pasche and Sköld 2012).

2.3.1 Platform assets

Components are the physical building blocks used when designing a product and designing component-specific tools for manufacturing (Robertson and Ulrich 1998). The product architecture is the interrelation between the components in the platform and can be modular or integral. A modular architecture is composed of clearly discrete modules where modules and parts meet a few functional requirements each (Ulrich 1995). In an integral architecture, one module or part is used to provide many functions. An integral product architecture with a large number of interfaces has the potential to create strongly connected systems and a predictable set of functions and implementations. It is more difficult to replace and refine the module separately from the product in an integral architecture.

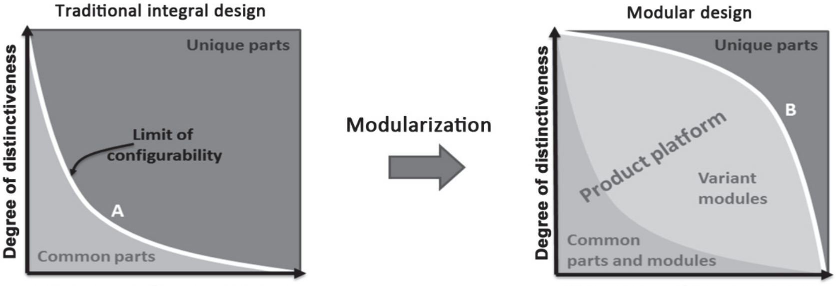

Figure 6. *Integral and modular product architecture based on Robertson and Ulrich's (1998) trade-off between distinctiveness and commonality (Jensen 2013).*

Robertson and Ulrich (1998) described the ideal modular architecture as using modularity to create distinctiveness, but also maintaining a high percentage of common parts in the product, curve B in Figure 6. A modular product architecture can reduce the interdependency between components yielding a stronger potential for economies of substitution (Pasche and Sköld 2012). Most products are a combination of an integral and a modular architecture that render specific functions both through the components and the modules (MacDuffie 2013). Variant modules can be stored in the platform as commonalities (Jensen 2013), Figure 6.

To produce customized products efficiently, facts about production *processes* are gathered and refined to form the process asset of a platform. Design processes are built up of deliveries and add to information in engineering design. Process assets have a structure from which variety in diverse products can be differentiated (Jiao et al. 2007). Design processes for platforms are described in more detail in section 2.1.

Knowledge sharing is a complex process and is practiced in construction mostly through local networks and oral communication (Kivrak et al. 2009). According to Styhre and Gluch (2010), the knowledge asset is a mechanism for bridging between the stocks and flows of knowledge in construction organisations by integrating know-how and experience of activities. To manage knowledge transfer between projects, central systems that link organisational knowledge with task completion, in order to produce project differentiation, enable both short-term performance improvements and long-term benefits in the development of construction firms (Bresnen et al. 2004). Experience feedback is described in Paper IV as the knowledge flow which develops platforms over time. Experience sharing, either in the form of a pull from actors or systematised for continuous improvement when it is needed, can help to minimise data loading. The ability to manage construction projects can restrict the management of knowledge in the organisation, because much of the collective experience disappears when a construction project is finished (Styhre and Gluch 2010).

Relationships in the MTO context initially relate to people working on platform organisation for product development. These people are organised in cross-functional teams with the task of either developing product families or diffusing common solutions throughout the whole range of products (Muffatto and Roveda 2000). Also, relationships deal with the relationships with other companies in the supply chain, where some actors are more closely coupled to the platform than others (Green et al. 2005). Integrating suppliers in the design work, places demand on relationships from long-time perspectives and a whole product realisation perspective (Tseng and Jiao 1998).

2.4 Product platform development and use

The combination of knowledge from product experts together with experience from project and product development is a foundation for platform development (Karlsson and Sköld 2007, Alizon et al. 2007, Wortmann and Alblas 2009). In a MTO context, derivative products are generated from the platform by releases that are to be put into production, Figure 4. Product and platform development is separated from production in an MTO supply chain. The platform is either developed by extensions of the same subsystems or into new versions of the platform (Simpson et al. 2006). As mentioned earlier, one of the main challenges when developing platforms is to balance between commonality for simplicity and costs, and distinctiveness for uniqueness and variety. Platform planning, according to Robertson and Ulrich (1998), involves a *product plan* for options, a *differentiation plan* to make sure that the models differ to attract customers, and a *commonality plan* that describes where products in the plan share the same physical elements.

Decomposing the platform into modules is a method that separates and stabilises interfaces and has also been proven useful in construction (Jensen et al. 2012, Miller and Elgard 1998). The idea of modularization is to define the boundary between modules, using interfaces, with a tight dependency between components inside the module and a loose interdependency between modules. The drivers for modularization differ between stakeholders and, for the same product, could define different module boundaries (Ericsson and Erixon 2000).

2.5 Design processes in industrialised house-building

Vrijhoef (2009) proposed that all construction operations in a supply chain could be connected as if they were a factory without walls. Design work in house-building can, from a project management perspective, be seen as a combination of project development, production planning and coordination of the design process (Winch 2003). Design activities are the decomposition of a product or service into solvable tasks and their subsequent solutions. Predefinition of design processes divided from overall stages down to activities and operation tasks meet the challenges of planning rework and iterations. Design work in a production process is balanced between creativity and systematic processes, leading to iterative loops. Formoso (1998) described the details of processes, ranging from serial activities in stages to parallel activities, and the details of coupled tasks where planning is based on experience of the interdependency of each specific operation (Formoso et al. 1998).

As multidimensional work, design work in house-building satisfies client demands and production constraints. Managing the design work efficiently means balancing the development of predefinitions within projects and applying these to those projects (Styhre and Gluch 2010). Design management using predefined solutions means balancing outsourced and in-house resources in a process that is central to the entire supply chain (Johnsson 2013). In industrialised house-building, when making a wholesale process commitment, engineers must manage not just the technical competence of how the building is designed and produced but also cooperative capabilities such as knowledge transfer, the ability to develop trust and meaningful negotiation, as well as competencies in information processing, communication and intra-unit and inter-unit coordination (Johnsson 2013, Gustavsson 2013). To manage house-building projects efficiently in decentralised organisations, a systematic approach starts with trust, communication rules and the use of teams to develop long-term relationships. To manage co-located, but especially dispersed teams, support methods do not only apply to the technical solutions but also to the corporate supports (i.e. tools, infrastructure, policies, rewards and incentive schemes) and their link to the project goals (Verburg et al. 2013).

Lessing (2006) defined industrialised house-building by focusing on the internal production process and noted that efficient organised production of complex components gives value to the customer. By controlling the design process in industrialised house-building and making that process more efficient, a higher quality of product development is achieved and so re-planning of design work is avoided. Repetitive processes in design provide a basis for treating those processes as commonalities in the process platform asset.

Magent et al. (2009) showed that engineering the design process through a network of decisions to produce the desired functions of the building adds value back to the design process.

> *"Understanding the design process as a network of decisions reveals the fact that models of the building design process provide little more than a coarse set of milestones, broad categories of design decisions, and sequential building systems analysis."*
>
> *(Magent et al. 2009)*

In industrialised house-building design work, systems to manage the process and related flows are important for reducing costs and increase production flow (Johnsson 2013). Stage gate processes are one underlying strategy with the benefits of securing planned progression (COBIM 2012). The decomposition of house-building processes into activities in a breakdown structure facilitates control over the progress deliveries from the work. For industrialised house-building design, the overall process commitment is an enabler for breaking down the process into activities and tasks (Pan et al. 2012). Internal and external stakeholder interests are central here for how decision-making produces construction design solutions. Stakeholder influences vary across different process stages in construction projects (Atkin and Skitmore 2008) and an ability to track these through the building life-cycle can give opportunities to define the related design process.

2.6 Platform use for house-building

In the last ten years of development of the house-building industry in Sweden, the product platform concept has emerged from theoretical concepts to become real strategies for construction firms to use (Johnsson 2013, Styhre and Gluch 2010, Thuesen and Hvam 2011, Veenstra et al. 2006).

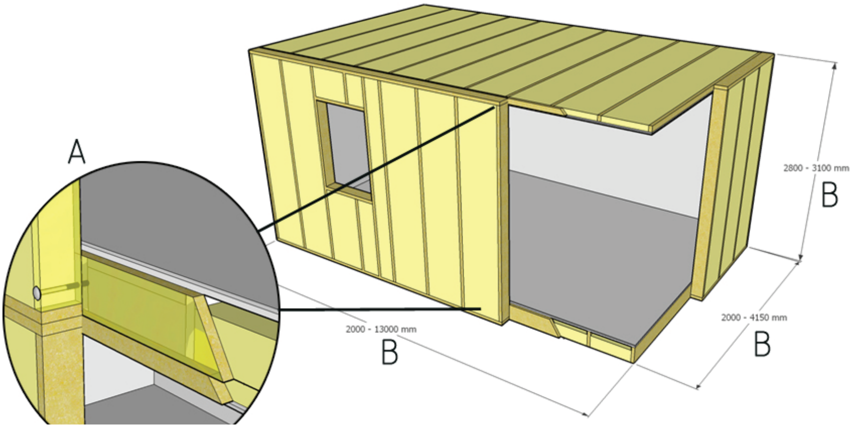

Figure 7. *Platform predefinition for timber house-building module with commonality in interfaces (A) and distinctiveness in module dimensions (B).*

In prefabricated timber house-building systems, products are stored by distinctiveness in dimensions (B in Figure 7) and thus chosen according to the client and site requirements (Höök 2006). Module interface standardisation through commonality (A in Figure 7) together with component independence and loose connections between modules produce a variety of design according to Voordijk (2006). To service a market that changes over time with clients who do not always describe their needs clearly, the stored knowledge in platforms does not only have to help design a variety of different house-building modules, but also help designers understand how interfaces change over time (Veenstra et al. 2006).

A wholesale commitment to house-building means responsibility for a product delivery which results in demands on the entire supply chain. Predefined processes and supplier relationships have an impact on the product output performance; using a house-building platform has revealed the importance of managing manufacturing lead times, customer response times, delivery to the client on time, deliveries from suppliers on time and client satisfaction in the product variety and quality (Halman and Voordijk 2012). The concept of house-building platforms is therefore extended not only to the management of physical parts but also to how the design and production work is organised to utilise the flow of knowledge in developing working processes for the supply chain (Styhre and Gluch 2010). By using continuous experience feedback from projects, development of the house-building platform could be carried out by analysing performance, process improvement ideas, relationships with clients and the project environment (Lessing 2006).

2.7 Research questions

House-building design work is the crucial part of the house-building production chain where project requirements (client, site, regulations) meet predefinitions (components, processes and relationships). To identify systematisation for platform use in day-to-day design work, the following question is posed:

> **Question 1:** How are platforms used to support design work in house-building?

Exploiting a platform that is not fully predefined, but leaves parts open for project specific creativity, has been beneficial in terms of an increasing market share. Thus, a platform that is not fully predefined seems to handle project variability well over time. To communicate changing demands, engineers have to master not only technical project design work but also the ability to cooperate. To identify the drivers of platform development over time, the following question is posed:

> **Question 2:** How are house-building platforms continuously developed to meet changing demands over time?

3 METHOD

The purpose of this chapter is to describe the research approach, strategy and process by explaining the methods and applied analytical approaches used. There is a description of the practical process and an overall consideration of the choices made during the research process.

3.1 Research approach

In this thesis, a systematic view of engineering design is applied to the context of industrialised house-building design. The field of engineering design describes design processes and how these support the realisation of products using technical support systems (Pahl et al. 1996). Technical support systems within engineering design are found across the whole field, from platforms to design processes (see Figure 19). Production theories have been used in this thesis to position the studied context as ETO. In this thesis, company management strategies in the form of lean production (Paper I) and mass customization (Paper V) are treated as emerging from the selected case studies and affect the way companies handle their platform.

3.2 The researcher

With a background as a software application engineer of design software in the construction and mechanical industries, my pre-understanding of design work on a detailed level enabled me to collect and sort data from the case companies' design work. As an instrument for the study, my pre-understanding and my knowledge gave access to a large amount of empirical data from the companies. Interest and pre-understanding in a field can also create bias in the collection of data and, therefore, multiple data sources and structured data collection methods with research protocols were used to counteract any such biases (Voss et al. 2002). Starting with empirical findings from an inductive research approach to industrialised house-building design, the contextual base presents a research opportunity to propose new theories (Denzin and Lincoln 2005, Meredith 1998). The difficulties of an inductive approach with data collection through case studies are making distinct demarcations and a risk of treating findings subjectively (Denzin and Lincoln 2005).

At the beginning of my PhD studies, the focus of the research was on how the design process in industrialised house-building could be made more efficient, from a very practical perspective. My focus on efficient software solutions and tool-based work resulted in an analysis that lacked the underlying theory for systemising design work. Industrialised house-building design lacks a theoretical foundation (Pan et al. 2012, Johnsson and Meiling 2009, Roy et al. 2005). The theoretical gap was identified using house-building as an example of an ETO scenario and so the research approach changed from finding solutions to analysing how platforms are used, developed and integrated with design work in industrialised house-building. To understand platforms in an ETO context, research into different house-building contexts was needed. The two case companies operate platforms where design work is carried out in-house in a design-build contract. In this thesis, design work is therefore further analysed and discussed as a production activity (after the CODP) and separate from platform development (before the CODP).

3.3 Chosen research strategy

A qualitative approach is suitable for studying platforms used in industrialised house-building as they arise in a natural context and the intent is to understand underlying structures (Guba and Lincoln 1994). The qualitative approach was therefore chosen to find answers to how the platform concept originating from MTO production strategies is used and developed in an ETO context as demonstrated by house-building design work. To further describe how platforms support day-to-day work and are developed over time, rich empirical data were collected and different theoretical perspectives of platforms were used. Case studies were chosen as the data collection method for all studies, to understand and describe findings in the context of house-building. A quantitative approach to the study would have had the ability to produce clear and proven statements (Miles and Huberman 1994), but to describe platforms in the context of house-building, case studies were chosen as the best strategy to create an understanding of the phenomenon and its practices (Yin 2003). By observing and documenting a variety of building project elements (e.g. planning design work, standardisation of components, feedback meetings), different theoretical perspectives (e.g. platform development, axiomatic design, modularity) were applied (Yin 2010). A combination of quantitative and qualitative data was used in all four studies to triangulate data sources (i.e. interview transcriptions, observation notes, archival data, project protocols and platform templates).

3.4 Research conducted

The work started with field findings from observations, archival data collections and meetings with company staff using an inductive approach (study 1). In the context of house-building design, where rules and routines change from project to process organisation, case study research has the strength to capture this phenomenon early in the study and then use it to form new theories using contextual data derived from both physical (in Study 4) and organisational elements (in Study 2 and 3) (Yin 2010). The theoretical framework of engineering design and platforms was established both in a previous literature review and in study 2. Deductive studies based on this framework were made in Papers II – V. The function of the case study was to examine design operations based on platforms used by companies, by looking at day-to-day design work, then considering and analysing platform use and development supported by the frame of reference. This approach created the means to generate new theories for the overall study (Voss et al. 2002).

3.5 Companies chosen for the case studies

The use and development of house-building platforms were chosen as the unit of analysis. Industrialised timber house-building companies have grown quickly in Sweden over the last 20 years after the removal of restrictions on the manufacture of multi-storey timber buildings. The company chosen for the case study, Lindbäcks, was therefore interesting because of their high level of predefinition using a systematised ETO supply chain, similar to an MTO scenario. NCC was the other company chosen; they use several platforms and have an overall process commitment to their projects, presenting an opportunity to analyse contextual data in the development of their house-building platform. Furthermore, NCC is a large contractor, which enabled an analysis of knowledge flow in the organisation using experience feedback. NCC operates a decentralised ETO supply chain, similar to a concept-to-order (CTO) arrangement.

3.6 Case company Lindbäcks

Lindbäcks started to take advantage of the change in regulations in 1994 that allowed taller timber buildings; to date, it has built over 7,100 apartments in multi-storey timber houses.

Figure 8. *Two studied projects realised by Lindbäcks (Björkbacken to the left and Långskeppet to the right).*

Lindbäcks is a family-owned company with a turnover of around 70 million euro and 170 employees. It manufactures over 1,500 apartments per year. The building system is based on prefabricated timber-framed volumetric modules that form the load-bearing structure. Windows, doors and façades are assembled at the factory together with elements that handle services such as electricity, ventilation and plumbing. The modules are completed with bathrooms, kitchens and optional permanent furniture. Modules are transported by trucks to the building site for assembly and completion.

The entire manufacturing process from contract to assembly and completion on-site for a medium-sized project (160 modules) is about 30 weeks. With a rate of production set at 40 modules per week, a medium-sized project needs 16 weeks for the design, 4 weeks for factory production and about 10 weeks for completion on-site.

The clients are municipalities, private clients, developers and the own real estate company. The house-building products are condominiums, rental apartments, student apartments and retirement homes, always in projects with wholesale commitment under design build contracts.

3.6.1 Unit of analysis: Design phase and working methods at Lindbäcks.

At Lindbäcks, planning and execution of the design process is central to the matching of production variants, client attributes and design resources, and the running of parallel projects. A breakdown structure of design processes into activities along with a way of managing the flow of process time, status information and distribution have been created by the company itself.

Figure 9. *Design Planning (Lindbäcks, 2012).*

Planning is carried out with a pull perspective, where design activities and deliveries have been deconstructed in a work breakdown structure (WBS) with associated delivery times. The support methods *design planning, collaborative design, design optimisation* (Paper I and Paper II) and *modularization* (Paper V) are used and were chosen for analyses in this research.

3.7 Case company NCC

The studies at NCC have been limited to the design process for house-building projects using platform standardisation. NCC Boende was the client in all cases. NCC is interesting because of their strategic investment in industrialised methods and continuous development work. Cross-sectional case studies were carried out at NCC Boende, NCC Teknik and NCC Construction on an operational level. On a strategic level, the development of platforms was also studied. House-building production at NCC accounts for a turnover of about €800 million per annum. NCC Boende is the client, acting as developers in the house-building supply chain.

The house-building projects studied were ones where the project group used their technical platform for day-to-day engineering and management of design work. Projects with wholesale commitment were chosen for the case study.

Figure 10. *The two projects by NCC studied: Marconi Park (left) and Kvillebäcken (right).*

Historically, NCC has invested in industrialised house-building. Prefabrication in a factory producing concrete elements for a predefined building system was developed in 2005. However, the factory was forced to close even before full production was achieved. The knowledge gained from this large investment has not only been transferred to concept-house production, but also to platforms.

3.7.1 Unit of analysis: Design organisation and working methods, NCC.

A project-based organisation using a predefined platform in design work was the unit of analysis. The design support methods for managing the design work were analysed in Paper II and Paper III: *design planning*, *collaborative design*, *design optimization* and *requirements iteration*.

The support methods were studied to understand platform use, while platform development was captured by examining methods of experience feedback (Paper IV).

Figure 11. *Design collaboration at NCC (NCC Projektstudio).*

The whole platform-based process gave an understanding of how a platform is continuously developed using experience feedback, but also how a systematisation of creative design work (iterations, meetings, decision-making etc.) could be established using a platform.

3.8 Research process

To achieve the overall aim of the research project, studies have been designed, planned and carried out. Research questions aimed at answering diverse platform topics were developed in each study, Papers I – V. Two main studies were carried out (studies 1 and 2) to understand platform use and support methods; the two later studies (3 and 4) were carried out to analyse platform development. Studies 1 and 2 answer research question 1 in Papers I, II and III. Studies 3 and 4 answer research question 2 in Papers IV and V.

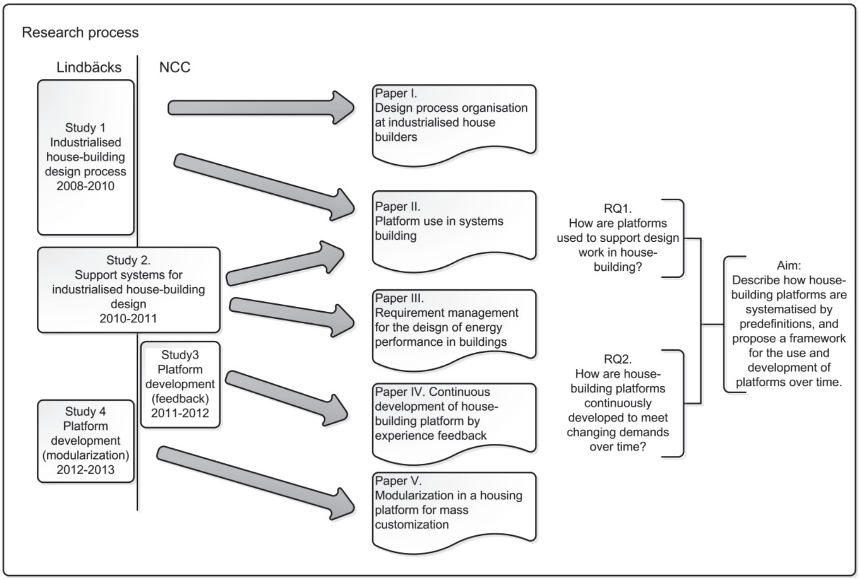

Figure 12. *Research process.*

3.8.1 Study 1. Industrialised house-building design process

To understand the industrialised house-building design process, an inductive case study with a qualitative approach was chosen to benefit from the rich descriptions of platform use in its natural context (Miles and Huberman 1994). A case study was conducted at Lindbäcks, following the design work through an archival analysis of project documentation. The case study had an exploratory study approach, which allowed for further research and the mapping of design work systematisation (Yin 2003).

Project managers and engineers at an operational level were interviewed (see appendix 1) in semi-structured interviews with open-ended questions, in order to allow the respondent to describe a picture of the design work freely (Kvale 1995). A triangulation of archival data was made with data from the first round of interviews. This resulted in a mapping of the house-building design work (technical report, Jansson 2009) and specified themes for interviews in the second round. The two companies, Lindbäcks and Moelven Byggmodul, have identical production systems, see section 3.5. The second interview round (see appendix 1) was carried out using structured questions to explore the design process and the decomposition of activities. The data were analysed using lean principles applied to the management of the design process, resulting in Paper I and a licentiate thesis (Jansson 2010c). The second analysis of the data focused on the standardised work processes at Lindbäcks, where activities were categorised in project-specific or platform solutions, resulting in contributions to Paper II. Notes were taken during the observations of day-to-day design work, at meetings and during the platform development work. Themed interview guides (i.e. platform use, support methods and experience feedback) were used both as support for filtering but also for the direct analyses of observations (Flick 2009).

3.8.2 Study 2. Support systems for industrialised house-building design

The aim of study 2 was to analyse the use of platforms in industrialised house-building and how the design management of house-building projects is carried out through day-to-day use of platforms. A deductive case study was designed, examining the theoretical gap of platform use in ETO scenarios, using NCC and Lindbäcks as the companies being studied.

At NCC, qualitative data were collected through interviews and observations. By selecting respondents from projects (operational) and development (strategic) levels, and allowing them to describe the use and support of platforms, the use of platforms from a supply-chain perspective was captured (see detailed selection of respondents in Paper II, Paper III and appendix 1). Design processes, platform use and support methods were the themes that directed the questions in the interviews. They were also the foundation for observations of five project meetings during spring 2011, see appendix 1. Quantitative data were also collected, at Lindbäcks and NCC, from documents, business systems and predefined rules in templates on computer-aided design (CAD) and customer relationship management (CRM) systems.

For the analyses in Paper II, study 2 was complemented by interviews with the platform manager at Lindbäcks, investigating the process mapping of data from 52 house-building projects examined in study 1. The same set of interview questions was formulated as for platform managers at NCC (see appendix 1). Data generated from interviews were summarised afterwards so as to complement interview with notes and reflections. Interviews were documented with notes being taken at the same time and verified with each respondent. Transcripts of the interviews were analysed for themes to find both specific and general results (Kvale 1995).

The findings from study 2 were analysed in Paper II with the focus on platform use in an ETO context and how a platform can affect standardisation differently (components, process, knowledge, relationships). In Paper III, the findings focused on managing energy requirements through design work by supporting axiomatic design. The interviews with energy engineers were different from those with project managers, with open-ended questions on how energy design and calculations in a project are carried out. Questions were asked that focused on the design process, design solutions, visualisation of results, design phases and time, see appendix 1.

3.8.3 Study 3. Platform development using experience feedback

In contrast to studies 1 and 2, study 3 investigated a directed method for platform development, namely experience feedback. A combination of archival data collection and interviews was planned and carried out for study 3 in order to describe how platform development could be established using experience feedback. In this study, the archival data were the main source of data used to analyse experience feedback flow. The study focused on platform assets, product architecture, frequency of feedback and formulation of constraints in the platform. Interviews were conducted with four platform developers (one building developer, two process developers and one technical developer) at a strategic level, see questions in appendix 1. 10 house-building projects were studied at different stages of completion. The data from the house-building projects studied (project optimisation and client feedback meetings) were combined with general data from platform predefinitions and experience feedback methods (points of view and improvements meetings) and analyses of platform development theories.

3.8.4 Study 4. Platform development by modularization

A deductive case study of modularization was carried out to analyse the use of modularization in an industrialised house-building supply chain. Modularization was chosen because the method has been shown to be able to meet the demands of both client variety and repetitive production in MTO scenarios. 10 of Lindbäcks' house-building projects in production were chosen. Five modules were identified: bathroom floor, balconies, façades, foundations and stairs. These were outsourced to suppliers or sub-contractors. Described in Paper V, an analysis of the systematisation of components into modules identified the interaction between component modularization and different module drivers in the supply chain. The modules were also analysed by examining their interfaces and product architecture (modular/integral) to understand their applicability for modularization.

3.9 Evaluating research work

The major problem of establishing trustworthiness of the results is to specify the link between the studied phenomenon and the version as described by the researcher (Flick 2009). To evaluate the work, Guba and Lincoln (1994) proposed a framework using credibility, transferability, dependability and conformability, a framework that has been employed.

Credibility strategies are, in this work, likelihood activities, peer debriefing, case use, appropriateness of the term 'understanding' and continuous member checks. By combining observations of the design work at industrialised house-building companies together with interviews and archival data, credibility by triangulation was established. Peer debriefing is a conceptual model employed by the research group and by the researchers at the competence centre LWE, where frequent academic seminars and meetings have tested and validated data about platforms for industrialised house-building. Close contact and frequent meetings with the companies (Lindbäcks and NCC) has meant that further analysis of member checks and projects has been possible.

Transferability is the degree to which findings can be transferred to other settings or contexts (Flick 2009). This research has been conducted in close collaboration with Lindbäcks, a centralised organisation that runs a factory with high levels of prefabrication. Furthermore, NCC, which is one of a number of decentralised construction organisations in Scandinavia, participated. Both companies have a unique set-up of suppliers, processes, methods and products. It is important for someone who wants to transfer and use these results to understand the context of this research (Flick 2009). Papers I and II show how, in an ETO context, support methods can be applied in design work, where the company manages the design work in-house. Modularization and axiomatic design are both methods that can be applied to the ETO context, however, module drivers differs between stakeholders in the supply chain.

Dependability gives a measure of the clarity of the research methods used. By documenting methods, the dependability of data can be checked to see that they have been correctly collected, reduced, summarised, reconstructed, processed and verified with participants in the studies (Flick 2009). When studying platforms and design processes over a period of six years, the dynamics of a context have to be considered. Over such a long period, methods for planning house-building design change, the use of components based on templates with platform constraints in CAD systems increases and the use of suppliers within the development of new sub-systems (modules) increases. These movements towards a systematised platform development and its use affect data over time. Studies have been followed up with sampling and comparisons of analyses of archival data from platform predefinitions and project reports.

Confirmability is also described as objectivity. Choosing a qualitative research approach, subjectivity and the indications of bias become most important (Yin 2010). The researcher is part of a workplace providing critical analyses, stimulating integrated work with other research fields (functional products, logistics, construction management) and critically analysing research results based on theories to minimise subjectivity. To minimise misunderstandings by the companies, findings have been discussed continuously with the companies and researchers in the group. By being immersed at the company, an opportunity to follow the development work first hand was created. By choosing peer reviewed journals and conferences, validation of the research objectivity based on descriptive findings has been possible.

Theory building is limited without a broad selection of companies. However, a small number of cases create a deeper understanding (Silverman 2005). By applying different theoretical perspectives (i.e. design creation, modularization, knowledge management and platforms) to two different industrialised house-building company contexts, findings and understandings can be extracted for analyses (Yin 2003). Proposals for developing a theory from the research questions have been synthesised and are described in section 5. Analyses of both practical and scientific results from the appended papers have been carried out continuously during the work, first applied to one theory and validated with empirical data, then often applied to second or third theoretical analyses but from different theoretical perspectives. Analysis using multiple theoretical perspectives has been carried out both by the researcher and also together with co-authors and colleagues in the research group.

4 FINDINGS

This chapter presents the findings from the appended papers that answer the two research questions. The interconnected results of the studies are presented.

4.1 *How are platforms used to support design work in house-building?*

The results from Paper I, II and III show how difficult it is to apply strategies and theories from an MTO context directly to the ETO context. The conclusion of Paper I was that the use of lean production principles is not directly applicable to design work in house-building. The customized product of house-building, with its high variability of client demands and design work that is part of a production system with non-sequential processes, needs standardised procedures. A suggestion from Paper I was to separate project-unique (distinctiveness) activities from repetitive (commonalities) activities so that product knowledge and resources could be captured by the platform itself, not only by person working with the product. In platform theory (MTO), product development is separated from production. This is difficult to achieve in the ETO context in house-building (Paper II). In an ETO context, the entire platform is difficult to predefine (Paper II). Thus, project requirements (client, site, national, regional) and platform parameters meet in the engineering phase.

A conclusion from Papers I and II was that standardisation of processes should be focused on when working with a platform that is not fully predefined. If not fully predefined, the platform must contain tools to manage variability and contrast it with the constraints of the platform use in project. Paper III suggested a framework to manage design work between functional requirements (FRs) and design parameters (DPs) using axiomatic design. The framework provides both a structure to handle functional requirements (as demonstrated by energy) in a platform, constraints that restrict design space and a structure to support creative design iteration through a stage-based process. Using a top-down refinement of functional requirements, Paper III presented an evaluation of design parameters starting at early stages, which lead to new functional requirements where constraints represent both predefined platform constraints (e.g. level height 2860 mm) or project constraints from decisions taken in the process (e.g. air velocity in the air conditioning system). The analysis showed how qualitative functional requirements could be managed using spatial models in the process. Another discovery from Paper III was how engineers can use the framework to change, follow and visualise their functional requirements to yield better house-building solutions.

Components, processes, knowledge and relationships were identified as the collection of assets for house-building platforms that combine to form the product offer (Paper II). Design support methods for day-to-day engineering work were needed when using platforms in house-building in order to bridge between project requirements and platform parameters, Figure 13.

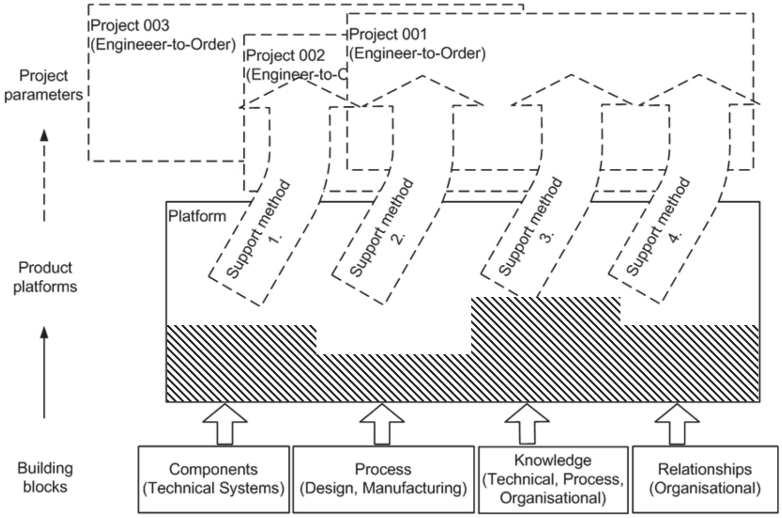

Figure 13. *Proposed platform model for an ETO context: how the platform supports projects.*

The support methods studied, *design planning, collaborative design, design optimization* and *requirements iteration,* all focus on different parts of the supply chain. Both NCC and Lindbäcks were at the stage of standardising components and activities in their platforms, by categorising commonalities for simplicity and cost reduction and categorising distinctiveness for uniqueness. The activities of the project managers, the engineers and the purchasing personnel were visualized with status with progression, Figure 9. Nevertheless, the companies differ in platform focus because NCC operates a fragmented platform (which does not yield economies of scale), distributed with many design instructions at a component level for design work. To the question of the review process for the support method of *collaboration design* and improvements concerning deliveries, the project manager said (appendix 1):

> *"If we move away from the current 14 day intervals of meetings to more frequent ones, one can set higher demands for higher speed for all participants in the design phase. But it is important that the client must also keep up. They often do not understand the design phase. There is a risk that if you reduce the time, the quality of the product suffers."*

The quoted demand for increased workflow was addressed through a back-end focus on production and supplier constraints (with fewer client choices). Both companies show a lack of platform standards that affects the entire production chain (from client to supplier in Figure 15). In Paper II, the need for a stronger focus on product knowledge in the ETO context (rather than in an MTO context) was identified. This focus is needed because the use of a platform has to embrace both structured platform knowledge and the knowledge to manage project variability.

4.2 *How are house-building platforms continuously developed to meet changing demands over time?*

A full separation of platform development and platform use is difficult in an ETO context (Paper II). Although it is possible to carry out product development outside projects, it is not always feasible since not all client needs are predictable, but arise when project requirements meet platform parameters in the engineering phase. In Paper IV, the following conclusions were drawn:

- Platform constraints need to be developed for the entire supply chain.
- The balance between commonality and distinctiveness has to be continuously developed and evaluated against the platform constraints for the supply chain (Figure 14).
- Platform constraints are developed over time if knowledge stocks and flows interact in the organisation (Figure 17).
- A clear purpose and direction of experience feedback channels creates the basis for trust in the platform and decreases data overflow.
- Channels for experience feedback should have different focus to create feedback not only concerning components, but also processes and relationships to support the entire platform.

To obtain an economy of scale for platform investments in an ETO context, the development needs to be systematised for the specific market segment.

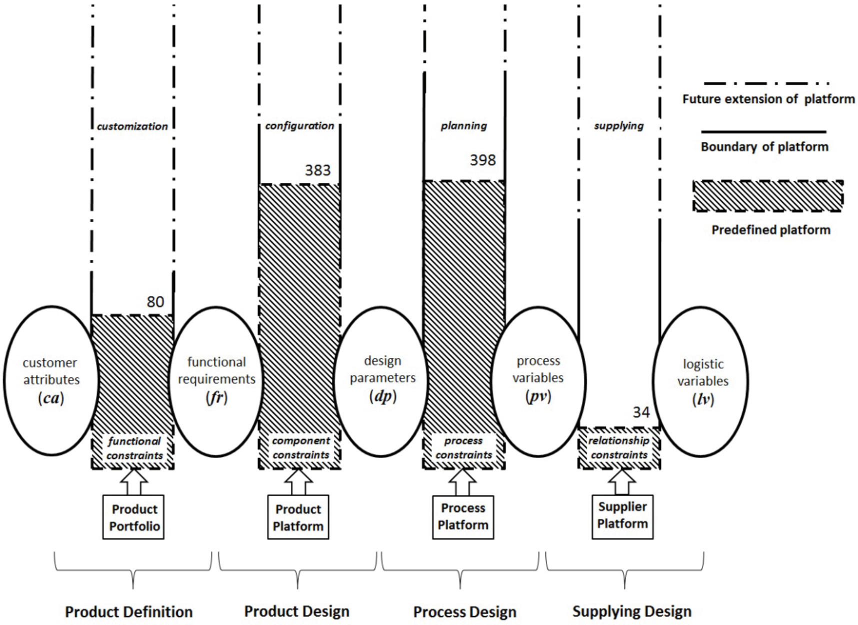

Figure 14. *Platform predefinitions (Paper IV).*

Systematisation of day-to-day engineering work is of interest for the development of a platform over time. In Paper IV, the constraints of the NCC platform were mapped as shown in Figure 14 following on from Jiao's (2007) mapping of product fulfilment. There were 80 functional constraints (steering documents), 383 component constraints (technical system), 398 process constraints (planning system) and 34 relationship constraints (agreements/contracts). Process constraints were the most documented in Paper IV and also the most critical for costs and workflow in house-building. Together with constraints, knowledge documents form part of the platform. In traditional construction, planning and execution of projects are carried out through a sequence of tasks encompassing concept, design, planning and contracting suppliers, upper part of Figure 15.

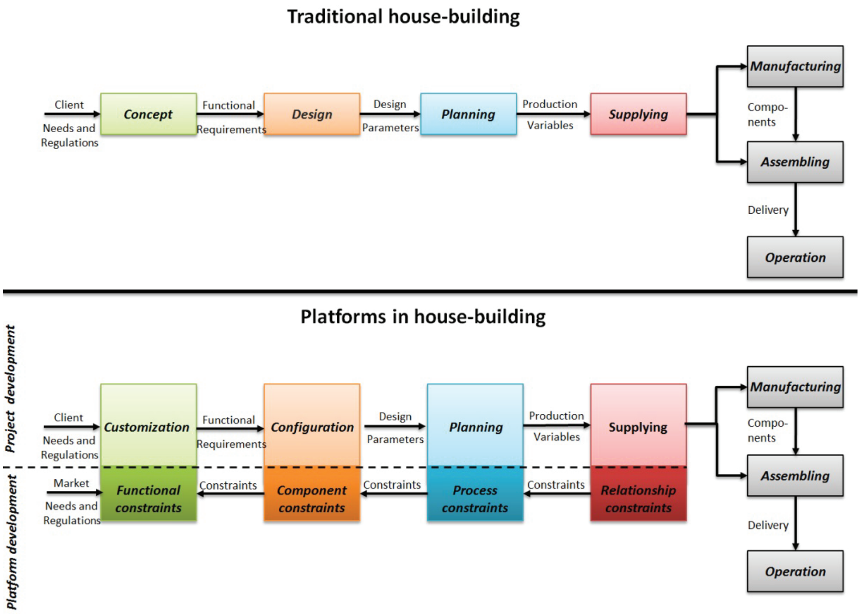

Figure 15. Platform systematisation of predefinitions in a house-building supply chain (Paper IV).

House-building platforms store constraints with knowledge between domains to support the day-to-day work of projects, Figure 15. Constraints, in the form of suggestions, requirements, demands and solutions, were proposed in Paper IV either to open up or restrict the platform. In platform development, relationship constraints restrict process constraints and planning for production variables (PVs), process constraints restrict component constraints and the configuration of design parameters (DPs) and, finally, component constraints restrict functional constraints and customization of functional requirements (FRs), Figure 15. Predefined platform constraints need to integrate between the domains to benefit from the investments.

In the continuous development, the balance between commonalities and distinctiveness has to be communicated throughout the organisation (Robertson and Ulrich 1998). Instead of combining commonality and distinctiveness into product families, Paper II suggested support methods to combine commonalities with project distinctiveness within the house-building platform. Site conditions as ground works and building silhouettes exemplify parts that create distinctiveness in a house-building platform. These are not fully defined and need support methods to produce distinctiveness without violating the commonalities that exist in the platform.

The use of modularization in a platform has the potential to allow both internal stakeholders, such as sales, purchasing, engineering and production, and external stakeholders, such as suppliers, sub-contractors and clients, to determine the specifications of a unique product offer. From the study of Lindbäcks' modules in Paper V, the use of parallel supply chains for suppliers gives the ability to increase the flow through the entire supply chain, Figure 16. In Paper V, the parameterisation of constraints in the modules showed how to meet both the client's wishes for distinctiveness and the production department's desire for commonality.

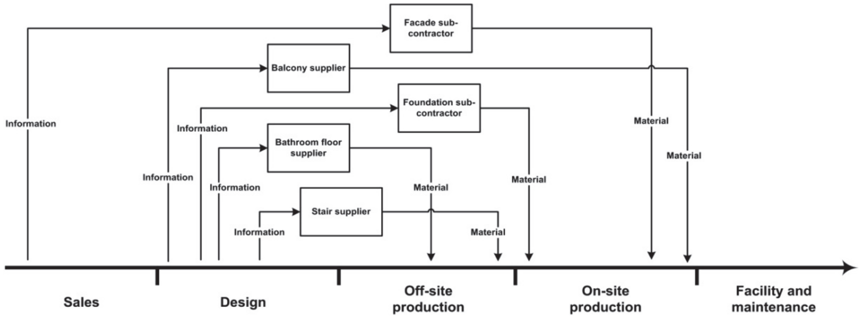

Figure 16. *Parallel supplier and sub-contractor processes for the five studied modules following the building process at the case company (Paper V).*

The study of five modules in Paper V showed the importance of evaluating modules based on their cycle times in the supply chain, Figure 16. Even if a module has clear interfaces and boundaries, the cycle time to produce the module in parallel (by supplier/sub-contractor) may not always fit the production flow from a process perspective. Suppliers and sub-contractors in the supply chain do have an impact on the process and how components fulfil the client offer. It is particularly important that they are part of updating the platform by communicating their experience.

Paper IV described how NCC developed their platform, recognising that there were long cycle times for house-building projects and a long time between feedback points. Paper IV showed the importance of integrating day-to-day feedback from projects with a continuous platform development. On the question of how experience feedback is managed in the organisation, one project manager expressed the need for systematising design work for newly employed project managers (appendix 1 study 3):

> *"I get along fine, but how can we help those who are new and which models do we have for various projects? There we have less experience. A listing of how we work in the early design stage and how it can be used is necessary. If anyone can place and update this in a solution, it would be good."*

Paper IV identified that a platform constitutes the knowledge stocks of an organisation and that the support methods and experience feedback that transport knowledge between the platform and the project can be considered to be the knowledge flow, Figure 17. The continuous development through experience feedback in the case study shows that direct feedback, separate from projects, gives fresh data from the supply chain for improvements of the platform.

Experience feedback in the case of NCC is based on continuous improvements by incremental steps in a Kaizen approach. The observations show how data and analyses of the entire supply chain are a valuable source of data for development. Experiences are stored in the project group or through individual knowledge in house-building (Bresnen et al. 2004).

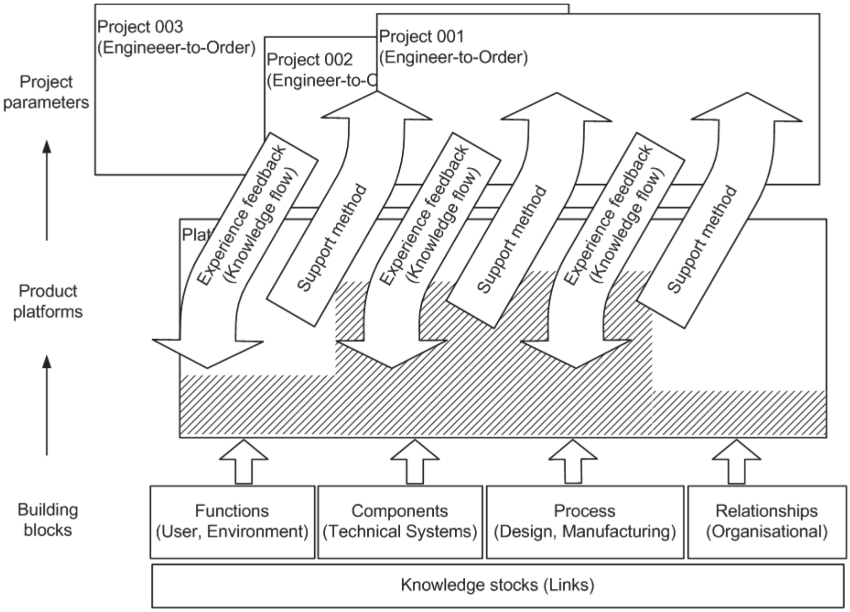

Figure 17. *Continuous development and use of house-building platforms (Paper IV).*

Continuous experience feedback is described as knowledge flow, in Figure 17, running from projects down to the platform. The case study at NCC showed how experience of every project was fed back once or twice, but mostly after the project was completed, resulting in long cycle times. The ability to manage construction projects places demands on not only how knowledge is stored in a platform but also how it flows in the organisation, because much of the collective experience disappears when a construction project is finished (Styhre and Gluch 2010). In Paper IV, it is suggested that experience feedback is used as a pull to update and develop the platform, thus taking into account its use, purpose, position in the supply chain and its effects on other constraints.

5 PROPOSALS

This section presents proposals for a better understanding of house-building platforms.

The aim of this thesis is to describe how house-building platforms are systematised by predefinitions, and propose a framework for the use and development of platforms over time. Two models describe house-building platforms: *Platform systematisation of predefinitions in a house-building supply chain* (Figure 15) and *Continuous development and use of house-building platforms* (Figure 17).

5.1 Platform systematisation of predefinitions in a house-building supply chain

House-building platforms enable companies to move from pure customization towards mass customization (Johnsson 2013). The benefits of reducing costs (in development, manufacturing and purchasing) and improving tailored products through services and standards in the platform (Robertson and Ulrich 1998) have to be weighed against the risk of losing innovative capability, the risk of imitation from competitors and the danger of resistance from within the organisation as a result of standardising engineering work (Haug et al. 2009). Project managers in NCC expressed the need for storing and systematising the design work. Both managers had recognised the benefits of using the platform but from different perspectives. In the other case, Lindbäcks, with high levels of predefinition, uses a platform to increase speed and flow, which could create a risk of solely focusing on constraining components in the platform. Constraining the products offered could narrow the potential market so platform use and development is a balance of predefinition for house-building.

A common theme in all five papers is the balance between creativity (distinctiveness for variety) and platform standardisation (commonalities for low cost) in day-to-day design work. The balance between commonality and distinctiveness in product solutions does not only affect components, but also processes and relationships with suppliers. Modularity is useful in balancing commonalities and distinctiveness (Paper V). By using commonalities for interfaces (A in Figure 5) and modularity for dimensions (B in Figure 5), the module becomes replaceable and the architecture becomes modular (MacDuffie

2013). Balancing between commonality and distinctiveness, by using modules in the platform, enables the company to position the product on the market or enter new markets (Erixon 1998). A result from the use of modules in house-building, described in Paper V, was the impact on customization of different client needs and regulations and how these affected the balance of project and platform predefinitions. Constraints formulated as solutions (commonalities) limit variability in platforms and constraints formulated as requirements restrict platforms with options (distinctiveness) for variability.

As described in Paper III, NCC had predefined functional requirements for energy-related designs in their platform, based on national and regional regulations, along with rules with default values for engineers to use in design calculations. Functional requirements were described in Paper IV as constraints that defined the platform. The ETO context here is hugely different from an MTO supply chain. In an MTO context, client requirements are not managed in the production supply chain and are not supported in the product platform. In an ETO context, one not only has to manage the variety of components, processes, knowledge and relationships in the supply chain, but also the transformation of functional requirements not predefined in the platform. It has been shown how project design work has the potential to manage non-defined parameters and combine them with knowledge stored in platforms in the process of house-building (Styhre and Gluch 2012). The use of a platform in the ETO context does not become a configuration system but a framework to manage the combination of design activities (creative and systematic). The ETO context, therefore, needs the platform to store constraints linked to knowledge and support methods and be used to transform these into design parameters, processes and supply chain variables.

5.2 The use and development of house-building platforms over time

The platform framework describes two different knowledge flows: a transformation flow that supports the use of the platform in house-building projects (Paper II) and the other an experience feedback flow from house-projects that develops the platform (Paper IV), Figure 17. The result of organising the house-building production chain to create flow for specific customer values is increased transparency and a higher output flexibility for both planning and management, Paper I. The house-building design process, combining creative and systematic activities, is not easy to describe as a sequential process and needs to be broken down and analysed for each specific production chain. NCC has developed methods to manage creative work through *design collaboration* (Figure 11) and Lindbäcks has developed methods for systematic design using *design planning* (Figure 9). Support methods serve as a bridge between platform and day-to-day design work in projects, Figure 17. Without support methods, there is a risk that project-specific variations in the day-to-day work slowly cause routines and defined processes to degrade. Knowledge flow from the platform to projects describes the day-to-day engineering work in industrialised house-building, Paper II.

Results from Paper II showed that support methods are necessary for the transformation of partly defined components and partly defined processes in the partly defined supply chain into customized buildings. To enable a systematic way of carrying out design activities, underlying structures in the platform could be developed to support specific work in the supply chain (e.g. requirements framework, Paper III).

In Paper IV, continuous development of a platform was analysed where constraints in the platform were updated and continuously developed to adapt to new technology, new demands and different project requirements. The importance of interaction between knowledge flow from day-to-day work and knowledge stocks in the platform was identified in Paper IV where the results of analysing push and pull for experience feedback channels in house-building were presented. One important parameter for a knowledge flow is how frequently feedback is returned to the platform, because the long cycle-times in projects and few feedback points lead to out-of-date platforms. By using channels, running from projects to platform development, that frequently update the platform, long-cycle times are avoided and fresh knowledge from house-building projects becomes accessible. The study of platform development in Paper IV shows how difficult it is to manage experience feedback in a decentralised organisation and how projects can be barriers to change and innovation when strategies for short-term task performance are chosen over long-term knowledge accumulation.

5.3 Platform framework

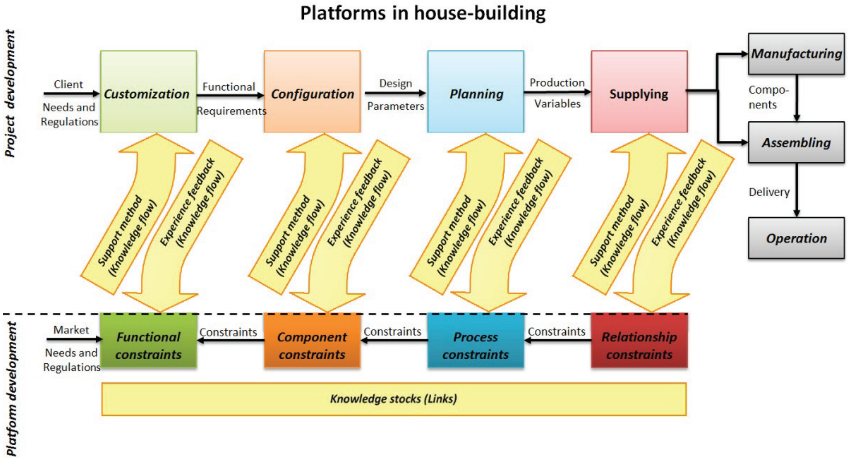

Figure 18. *A framework for continuous development and use of platforms in house-building.*

The ETO platform framework in Figure 18 shows the combination of knowledge from the creativity in design work (project development) and a systematised process in a product supply chain. Platform management implies that there is continuous parallel work to update and maintain platform definitions over time.

The platform framework describes house-building predefinitions that are created through integration of platform use and development. A framework for the use and development of house-building platforms is proposed in Figure 18:

- Client needs and code regulations are the input to maintain the balance between project and platform work (input for design).
- Design work is part of the supply chain (project part).
- The balance of commonality/distinctiveness is sustained and evaluated in projects (project part).
- Needs and regulations are supported in the customization of functional requirements (1st yellow arrow up).
- Functional requirements are supported in the configuration of design parameters (2nd yellow arrow up).
- Design parameters are supported in the planning of production variables (3rd yellow arrow up).

- Production variables are supported in the supplying of manufacturing (4th yellow arrow up).
- Methods that support frequent experience feedback are needed for keeping an up-to-date platform (yellow arrows down).
- Knowledge flows and knowledge stocks must be linked to keep an up-to-date platform over time (yellow fields).
- Commonalities and distinctiveness are integrated using functional requirements, component, process and relationship constraints (platform part).
- Systematisation of constraints in the platform is made separately from projects (platform part).

Project development is the day-to-day design work in house-building where the traditional underlying structures for planning, contracting, producing and controlling are based on project management. Industrialised house-building is a realisation process of products (a combination of project and platform development) which has the potential to use platform management as the underlying structure.

5.4 Platform proposals

When considering how house-building platforms are systematised using predefinitions, the following proposals are presented on how to manage *predefinitions* in a platform:

- Platforms can contain functional requirements as well as predefined solutions when applied in an ETO context, Figure 14.
- Knowledge forms the links in a platform, Figure 17.
- Constraints can be part of both commonality and distinctiveness, stored and managed in the platform, Figure 15 .

Proposals for the platform use are:

- Support methods are needed for design work in a partly defined platform, Figure 13.
- Customization can be supported both by creative and systematic design work in projects, Paper III.

The following proposals are made about platform development:

- Platform constraints need to be developed for the entire supply chain, Figure 15.
- Platform constraints are developed over time if knowledge stocks and flows interact in the organisation, Figure 17.

6 DISCUSSION

The chapter discusses the practical and scientific contributions of this research. The results are positioned and the research contribution discussed. Finally, some thoughts about the research work and results are presented.

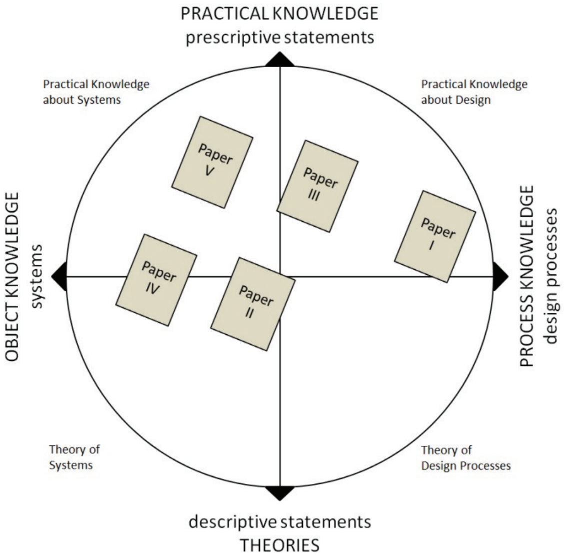

Figure 19. *Main categories of design* (Hubka and Eder 1996)

6.1 Positioning the results

Hubka and Eder (1996) described the constituent areas of design work as a tension between theory/practice and object/process, Figure 19. The research Papers I – V are positioned in Figure 19. The research ranges from systems knowledge to design process knowledge (horizontally) and from practical knowledge down to theories (vertically), Figure 19.

Paper I is positioned close to process knowledge in Figure 19, since the purpose was to understand design processes in industrialised house-building and identify problems of flow and transparency in design work. There were limited scientific contributions in terms of new theory in Paper I. However, the empirical study contributed to the understanding of how design processes are standardised and how repetition of work is related to organisational strategies.

In Paper II, there was a discussion of the use of platforms in the ETO context by establishing how support methods are used together with a partly defined platform when realising projects. There were two contributions. First, there was a prescriptive statement of how a platform could form a backbone for industrialised house-building. Second, the research in Paper II showed how a platform is used in an ETO context, providing a descriptive statement, Figure 19.

A stepwise fulfilment and evaluation of requirements, as demonstrated by energy design, was presented with a process perspective in Paper III. The axiomatic design framework in the paper described how requirements handling can be systematised. Furthermore, the organisation of design work as structured levels with gradual refinement of requirements formed a framework that supports the practical use of platforms in an ETO context.

Paper IV covers the long-term survival of a house-building platform driven by experience feedback. Balancing constraints in the platform and continuous platform development are practical statements that were verified by interviews, observations and archival data. Scientific statements in the paper describe how platform development in the ETO context differs from an MTO scenario and how the platform is continuously updated through knowledge feedback from project work.

In Paper V, the application of modularization as a complement to commonalities in a platform was screened. A case study that identified modules (bathrooms floors, balconies, façades, foundations and stairs) was carried out. Module drivers were presented emerging from the MTO context (Ericsson and Erixon 2000). It was proposed that the supplier cycle time for the ETO scenario is a complementary driver. Practical statements about how to use parameterisation, module drivers and cycle times for modules were made. The proposal of the supplier cycle time as a module driver, valid in the ETO context, formed a descriptive statement.

6.2 Research contribution

This research proposes a theoretical framework of how to use and continuously develop platforms for house-building. The research process has had the goal to contribute knowledge to the scientific community and practical applications for design work to the industry.

6.2.1 Scientific contribution

The scientific contribution is the underlying theoretical understanding of how the platform concept is applicable and sustained in the ETO context, as demonstrated by house-building. House-building companies suffer from low efficiency of deliveries where timing, cost and quality are not consistent with the use of resources (Tilley 2005). So, the platform concept from the MTO context (Meyer and Lehnerd 1997, Robertson and Ulrich 1998) has been adapted to the supply side of the house-building industry. The research in this thesis captures this adaptation and describes it in theoretical terms as proposals and models for further confirmation by other researchers.

The scientific contribution of this research widens the theoretical field of the use of platforms in an ETO context and expands the point at which the framework and proposals for industrialised house-building support design work for customized production. In Thuessen's (2011) study of a German house-building platform, the balance of the similarities in client functional requirements (commonality) and their varieties (distinctiveness) contributed to a development process, based around value definitions, within the platform for the repetition and handling of integrated markets, projects and processes. Functional requirements are identified in this work as one of the major determining factors of predefinitions that separates the platforms in the ETO and MTO contexts.

Company studies in the ETO context give an opportunity for generalisation but have to be analysed from the broad range of house-building that the ETO context provides. Product families in an ETO scenario have been shown to be unusable because not all the parameters are defined when clients enter the house-building design process. The balance between commonality and distinctiveness is, instead, sustained in projects.

6.2.2 Practical contributions

The practical contribution of this work is the understanding that industrialisation of house-building is more than prefabrication and that the platform concept allows a choice of what to industrialise and predefine from the product, process, relationship and knowledge perspectives.

In this study, knowledge was found to form the links in platforms through the support method "Design optimization", which both fed back experience to the platform and supported the design work in projects. This is described as double–loop learning in construction (Henderson 2013) and integrates both knowledge pull to the platform and knowledge push to improve projects. Such experience feedback needs a well-defined purpose with a knowledge pull to create direct and specific improvements (Meiling 2010).

The company strategy to use and develop the platform concept for mass customization entails the combination of commonality (to decrease production costs) with distinctiveness (to create client value), along with the integration of design work (quality and quick reaction to changes in the market) (Tseng and Jiao 1998). In house-building, where production and client meet in the design process, design work needs to be organised to combine and balance commonality and distinctiveness. The research has shown how two different companies manage the challenges of this combination and has also described what risks are present if the context is not carefully considered.

The applicability of the research can be seen in study 2. A concrete result of the studies is the way in which Lindbäcks has developed the process part of their platform framework to incorporate distinctiveness parameters (i.e. client type, building levels, project size, functional use etc.). This helps to plan the design work by detail planning and scheduling. Another practical contribution to the development of the platform over time was how NCC showed that experience feedback needs to be targeted in the development of an updateable platform. The advantage of using components in the form of type solutions was frequently exploited instead of using interface commonality in connection with production work and supplier instructions. The study showed how design work is central to the process when using platform predefinitions and how the motivation for design choices and their communication to production and suppliers has to be transparent across the supply chain from the definition of client requirements right through to production.

6.2.3 Linking contributions to the aim and research questions

The overall aim of this thesis is to describe how house-building platforms are systematised by predefinitions, then propose a framework for the use and development of platforms over time. The research questions enable the division of this aim into targeted investigations to find answers that fill both a scientific and a practical gap. The two research questions about platform use and development cover the underlying findings about how house-building platforms are systematised.

How are platforms used to support design work in house-building?

The question is limited to the support of design work and is not targeted towards management or control of the design work. The use of platforms originates from the MTO context (Simpson et al. 2006) and is useful for product development in areas such as the car industry. Such product platforms are not exposed to a specific rate in design or a demand for deliveries from clients. When using platforms for project development, support methods are needed both for managers and engineers to keep speed, flow and quality in design work. The cases studied showed two different approaches using platforms. Lindbäcks has a main focus on speed and flow whereas NCC focuses on the quality of deliveries. Design work support methods depend on how detailed the predefinitions in the platform are and how constraints are handled in the platform.

How are house-building platforms continuously developed to meet changing demands over time?

Platform development is theoretically separated from product platform development in an MTO context (Pasche and Sköld 2012) (Robertson and Ulrich 1998). This research has shown that the development of platforms in an ETO supply chain differs from that in the MTO context. Product development is integrated in the day-to-day work of projects in the ETO context (Jonsson and Rudberg 2013) and organised when combined with operational knowledge that is fed back to the platform (Styhre and Gluch 2010). The study shows how integrated day-to-day work in building projects has to handle changing demands. This can be seen as a problem in finding general structures when systematising work, but has also been shown to be an advantage, allowing creative design work for customized homes (Lu et al. 2011). Meiling (2010) described the continuous improvement over time from building projects as a problem of creating a knowledge pull instead of a knowledge push to create experience data. When there is a continuous development of platforms using project knowledge, there is a risk that project feedback applies to systems, instead of developing platforms using knowledge pull to adapt to the changing demands of day-to-day work.

6.3 Reflections on the research

The purpose of this research was to create knowledge by studying the existing reality. Reality is often not represented by a generic view of the phenomenon; instead, it changes over time and between contexts.

6.3.1 Reflections on research work

The presented framework in Figure 18 describes the development and use of house-building platforms in the ETO context. By using case studies of two different companies, the purpose was to analyse platform use and development with a qualitative approach to present contributions that could not be captured solely using statistical methods. The framework itself is not generic, because there are so few cases in the study, but describes those cases in detail. The final confirmation of the framework is therefore left to other researchers.

By using a qualitative research approach with observations, literature studies and interviews of operational personnel, a practical mapping of how to support and systematise design work based on a platform could be captured, instead of the imaginative view of reality that is often described by strategic and system developers (Yin 2010). By following the day-to-day design work at the companies, the researcher has been able to consider the use of a combination of creative and systematic work. Lindbäcks, with its centralised organisation and high predefinition of their production process, and NCC, with its decentralised organisation using support methods for the design process and experience feedback to improve the quality of deliveries, are two different companies with two different supply chains operating within the ETO context. A risk with industrial collaboration is that the researcher tries to find answers to questions that only support a subjective development of knowledge. The definition of the framework and related proposals have, therefore, been presented continuously to research colleagues, at conferences and seminars with international, national and regional industry partners, to minimise the subjectivity of the work.

6.3.2 Reflections on the results

In this work, integration of design work in the supply chain is recurrent. Construction in general, and house-building specifically, has a tradition of contract-based processes with islands between stages in the supply chain. A platform framework does not solve the issues created by interrelationships between stages but could be seen as a tool for industrialisation processes where wholesale commitment is demanded.

It has been suggested that the industrialisation of house-building might act as a driver to change companies from inefficient project organisations to organisations carrying out process-oriented, flow-based work (Winch 2003, Höök and Stehn 2008). The house-building industry extends from limited client choices, almost an MTO scenario, to near-total flexibility, as found in a CTO scenario. Across this range of supply chains, platform use and development have to be positioned in cooperation with a company's business strategy.

Suh's (2001) axiomatic domains are the basis of the platform framework for industrialised house-building. In the MTO context, platforms between the domains in product fulfilment support the definition of the product. Here, product portfolios are the bridge between customer attributes (CAs) and functional requirements (FRs) according to Jiao (2007), Figure 3. For house-building in the ETO context, not all the CAs and FRs are defined when the design is started and support for the first transformation is needed from the platform using predefinitions. There were about 80 functional requirements in the platform at NCC, Figure 14. These have also been identified as constraints in the platform framework with the purpose of supporting transformation to products in the form of houses. Only the transformation between the functional requirements (FRs) and design parameters (DPs) used in energy design has been applied and evaluated in this work.

Energy design, as an example, does not end with a physical product and research for energy needs to explain how new technologies, materials, systems and processes could improve design work. Systematisation of demands for whole-life and whole-system approaches does not follow traditional fixed-state scenarios and instead supports continuously changing processes, understandings and motivations for energy design (Schweber and Leiringer 2012). Design work has to fulfil stakeholder demands at all points along the supply chain, from client and customer on the demand side to production and logistics on the supply side. It has been shown that the platform framework can propagate not just components in the process but also client demands, functional requirements, systems solutions and layouts.

The use of predefined processes has led to reduced cycle times and efficient resource use (Thuesen and Hvam 2011). The need for a balance in the platform in an ETO scenario becomes obvious when predictability is limited by customization in the form of open parameters (i.e. building shape, on-site conditions, client choices, end user functionality etc.). It has been shown that the proposed platform framework can be used to manage not only commonality and distinctiveness but also modularity.

7 CONCLUSIONS

This section summarises the development of platforms and their use for industrialised house-building, with suggestions for further research in the field.

7.1 A platform framework for industrialised house-building

A platform framework was developed based on platform theories (Meyer and Lehnerd 1997, Robertson and Ulrich 1998). Transferring these theories from an MTO context and applying them in the ETO context revealed the following differences:

- the ETO supply chain can have design work integrated into production
- client requirement variety must be handled in the ETO supply chain
- the building project is a useful entity that can replace product families in the ETO supply chain
- functional requirements can form part of the platform for the ETO supply chain

In the industrialised house-building supply chain, integrated design work is the key. The day-to-day use of a platform in design work thus requires:

- wholesale commitment
- support methods for the partly defined platform
- a continuously re-evaluated balance of commonality and distinctiveness

Development of a platform in house-building requires:

- knowledge integration as the linking elements between assets in the platform
- a pull for project feedback to create an up-to-date platform
- continuous evaluation of platform use in the ETO supply chain to improve the platform over time

A house-building platform has been shown to support the day-to-day work in the whole supply chain from clients through to production and suppliers.

7.2 Further research

In this work, the use of platforms has been demonstrated in industrialised house-building, representing an ETO scenario. Research in the field of platform use for construction, where other building systems are used and different supply chain methods are employed, is of interest to further test the platform framework proposed in Figure 18. By limiting the scope of this research, such that the systematisation of commonalities and distinctiveness of components, processes and relationships are just briefly discussed and identified, allows for further research. The modularization concept has been tested for components and processes (Reijers and Mendling 2008, Baldwin and Clark 2006). Methods of using modularity in combination with processes in the supply chain should be studied further in industrialised house-building.

The empirical findings have also shown the importance of developing platform predefinitions from a supply chain perspective. Therefore, a suggestion for further research is to look into the management of constraints in supply chains and interrelations between constraints, both upstream and downstream.

Research into industrialised house-building has produced benefits for productivity when using platforms in production to enable the flow of material and information (Jonsson and Rudberg 2013, Meiling et al. 2012, Lu et al. 2011). The method of systematising and communicating platform predefinitions in the client organisation is key to the success of platform use in industrialised house-building. The benefits of the systematisation of client demands for house-building have been studied less often. It would, therefore, be interesting to understand how different production supply chains in house-building could address different market segments with a platform approach.

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PAPER I

Design process organisation at industrial house builders: a case study of two timber housing companies in Sweden

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Proceedings of the 24th Annual ARCOM Conference, September 1-3, 2008, Cardiff, UK

DESIGN PROCESS ORGANISATION AT INDUSTRIAL HOUSE BUILDERS: A CASE STUDY OF TWO TIMBER HOUSING COMPANIES IN SWEDEN

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In industrial construction companies the design process tends to be the bottleneck for further streamlining of the entire manufacturing process. The demands posed on this particular design process are diverse; should feed the production process with data, should satisfy the client with documentation and should document the project for experience feedback. Further complications arise from the internal notion of being a manufacturing company opposed to the external view of the company being a traditional building firm. In this work, the design process at two industrial builders was studied in-depth. The two companies have chosen opposing strategies for their design departments; one have specialised functions where all projects pass and the other have more general designers who work in parallel with similar tasks. With the support from lean production theory, the consequences of these two strategies on succeeding with design of industrial built houses are analysed. The results show that increased specialisation is beneficial in daily work, but can pose a sensitive design process if key competences suddenly vanish.

Keywords: corporate strategy, design process, housing, industrialisation, prefabrication.

INTRODUCTION

Industrialised housing is a growing market segment on the Swedish construction market with a market share of approximately 15 % (Höök 2008). The degree of prefabrication differs; single wall elements can be prefabricated as well as entire volume modules complete with interior claddings and equipment. When larger portions of the building process are harnessed by the same company, possibilities for streamlining the process arise. Later years have seen an increasing interest in lean construction (Koskela 1992). Industrialised housing was described by Lessing (2006) as having 8 characteristics; experience feedback, process control, developed technical systems, off-site manufacture, long-term relations, integrated logistics, customer focus and use of ICT tools. For industrialised house builders, the internal processes are best described by lean production, while the external processes belong to the lean construction framework (Höök 2008). In this study, two volume element producers are focused. They internalise the design, manufacturing and assembly processes normally carried out by different companies in an ordinary building process. Therefore a customer focus has to be placed on clients, subsequent activities as well as end customers. A common problem for the two companies is that the design process is

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the bottleneck for increasing volume in production. The aim of this paper is to analyse the design process at two industrialised house builders in Sweden through a lean production perspective.

METHODOLOGY

The decisive starting-point for the data collection were our research questions, “How is the design process organised?” and “How well do the respective organisations correspond to lean production principles? The unit of analysis was defined as the design process at two (specific) companies within industrialised housing in Sweden. Despite comparable settings on the market for both companies, the choice of strategy for organising the design process differs.

When choosing research design, case study research (CSR) was considered a suitable alternative, since the questions are “how” questions, we have little control over the events and focus a contemporary phenomenon in a real-life context (Yin 2003). In studies of how two companies in timber housing execute their daily work there are very little control over events for the investigators. The focus of this study is on a contemporary phenomenon within a real-life context. This is a multiple case study (of two companies) with a single unit of analysis (the design process) (Yin 2003).

Data has been collected using three different methods; interviews, archival analysis and participating observations at meetings. The interviews were all semi-structured in-depth interviews with 15 persons in total, 8 at Company A and 7 at Company B. (Functions of the respondents can be found in figs 1 and 2). Focus of the interviews was placed on the current way of working in the design process. The archival analysis was mainly focused on documentation regarding time scheduling for design projects. All in all, we participated in six meetings at Company A and seven meetings at Company B. Through the study, additional data has continuously been collected through an ongoing interview process. Identification of the need for additional data was made in a comparison between the two cases, but also when theoretical knowledge increases. At both companies there were designated contact persons for correspondence. Data from different sources were triangulated to increase the validity in the case. This was a well needed method since the models for organising the design process and associated activities were not directly observable at any of the two studied companies.

The material was then analysed through a Lean perspective, based on table 1. During this analysis, we realised that all diversities and similarities were consequences of choices made by the companies. Therefore it was essential for the study to find a theory capable of explaining differences in strategies. Mintzberg and Waters (1985) theory about deliberate and emergent strategies appeared to be usable.

Case study companies

Company A is a timber volume element builder specialised in products ranging from simple small booths, to office buildings, schools and multi-family dwellings. Houses built by Company A are mainly of four stories. Main customers are one large contractor in most of the multi-dwelling projects. The customisation degree is high due to several different factories. Company A has 300 employees allocated at four production facilities and an annual turnover of 42 MEuro.

Company B is also a timber volume element builder with specialisation in student lodgings, hotels, multi-family dwellings and senior dwellings. Houses built by Company B are mainly of four stories. Main customers are co-operative building societies, real-estate trustees and student associations. The customisation/standardisation degree is high within projects. Company B has 135 employees located at one production site and an annual turnover of 42 MEuro.

LEAN THINKING

The aim for perfection is the foundation of lean production. Central to the success of the lean production approach is the involvement of personnel, who are encouraged to see mistakes as possible points of improvement. The basic idea is simple – reduce unnecessary operations (waste) with uncomplicated methods to promote increased flow targeted at creating customer value. The notion that work organisation is directly coupled to the manufacturing strategy might be most pronounced in lean production (Womack and Jones 2003). Lean production is one of the manufacturing principles that have been transferred to the construction industry i.e. lean construction (Koskela 1992).

In Lean production the concept of value is central together with concept of waste. Everything not adding value is considered to be waste. Womack and Jones (2003) states that the aim is increased value in every process step. Value is defined as the price customers are willing to pay for a product (Womack and Jones 2003). Value can also be research and development generating value for strategically important choices in a long-term perspective (Höök 2008). Organisationally and strategically, value stream is central for the management in Lean Thinking. Resources, such as information, people, systems and work strategies, are necessary in a holistic perspective to achieve a better value stream in the design process (Rother and Shook 2003). Pull is the mechanism to deliver exactly what the customers need, at the time it is required (Womack and Jones 2003). Björnfot (2006) summarises the approach of Lean Thinking in eleven principles for flow in construction, which are related to increasing the transparency and output flexibility with values from the process. Planning and management are important in the process for flow with a reduction of non-value activities, variability, cycle times and unnecessary steps.

Lean Design is summarised by Jørgensen (2006) for publications about design in construction through the late nineties until 2006. The design management is focused in the publications, where theories about conversion, flow and value from Lean Construction are presented and Lean theories are based on the five criteria of Lean Thinking i. e. Brookfields characteristics of management for Lean Design (Jørgensen 2006). See table 1.

For the prefabrication of timber housing it is important to see how different approaches to Lean can be applied. Design for industrial timber housing can not be fully described, neither using Lean Production nor Lean Construction (Höök 2008). Koskela (1992) emphasises the importance of the “connecting parts” in the construction process, where people and information links create transformation, which is the major difference compared to Lean production theory (Höök 2008). Both customers and actors in the design process must be analysed in view of the construction context. Within industrial manufacturing of houses the reuse of information in the design process is low and the actual design work is made with site construction methods. The project related approach in Lean Construction can be necessary for design activities related to value generation.

Table 1. Model for evaluation, based on the five lean principles.

Conceptualisation in construction (Björnfot 2006)	**Characteristics for lean design (Brookfield 2004)**	**Evaluation criteria for obtaining a lean design process**
1. Value Define the customer Define what is value for customer Define what is value to the delivery team Define how value is specified by products	Identify value from the customer's point of view	1.1 Are customers defined? 1.2 Is customer value defined? 1.3 Is value for the design team defined? 1.4 How is value transparent in information and drawings?
2. Value stream Define all recourses for production Define all activities required for production Standardise current practice. Define and locate key component suppliers.	Understanding the value streams by witch value is delivered for the whole design process.	2.1 Are all resources for the design process defined? 2.2 Are all activities in the design process defined? 2.3 Are the processes standardised? 2.4 Are key information suppliers defined?
3. Flow Identify non-value adding activities (waste). Remove or reduce the influence of waste as it is observed. Identify key performance indicators. Measure performance.	Achieving synchronous flow within work processes as waste is removed.	3.1 Are non-value adding activities (waste) identified? 3.2 Is the influence of waste removed or reduced? 3.3 Are key performance indicators identified? 3.4 Is performance measured?
4. Pull Keep the production system flexible to customer requirements. Keep the production system adaptable to future customer requirements. Exercise a conscious effort at shortening lead and cycle times. Perform work at the last responsible moment.	Achieving pull so that no information is delivered until it is needed.	4.1 Are design systems flexible to customer requirements? 4.2 Is the design system adaptable to future customer requirements? 4.3 Are efforts in shortening lead and cycle times exercised? 4.4 Is work performed in the last responsible moment?
5. Perfection Keep the production system transparent for all involved stakeholders. Capture and implement experience from completed projects. Exercise a conscious effort at improving value for customers. Exercise a conscious effort at improving the execution of work.	Perfection - recognising that improvement needs to be constantly pursued.	5.1 Are design systems and routines transparent to all stakeholders? 5.2 Is experience from completed projects captured and implemented? 5.3 Are efforts made to improve value for customers? 5.4 Are efforts made at improving the execution of work?

Lean Construction theory as well as Lean Design, mainly focuses on traditional onsite construction with customer value at a project level (Lessing 2006). Strategical choices in the organisation of the design process at two industrial timber housing companies are compared against the criterions in Lean Production and Lean Thinking, table 1.

Björnfot (2006) states, that Lean philosophy can be applied to construction when a mixture of the five principles, represented in column 1, table 1, is at hand. In column 2, the characteristics for Lean Design according to Brookfield (2004) are presented. In column 3, the Lean criteria for evaluating design processes are presented, based on the theory characteristics in columns 1 and 2.

DIVERSITIES IN STRATEGIES

Strategy has been conceived in terms of what leaders of organisations ‘plan’ to do in the future. As long as there has been an interest in strategies within organisations, there has also been curiosity about the relationship between what is planned and what is actually done. Labelling these two phenomena in terms of strategy, Mintzberg and Waters (1985) make a distinction between *deliberate strategies* – realised as intended, and *emergent strategies* –patterns or consistencies realised despite, or in the absence of, intentions. Deliberate and emergent strategies are by Mintzberg and Waters (1985) described as poles of a continuum along where all real-world strategies could be expected to fall.

Mintzberg and Waters (1985) propose eight types of strategies: 1. *Planned strategy:* Leaders formulate their intensions as precisely as possible and then strive for implementation i.e. translation into collective action. 2. *Entrepreneurial strategy:* One person in control of an organisation and imposes his or her vision of direction on it. Since vision only provides a general sense of direction, there are room for adaptation of other visions within the organisation. 3. *Ideological strategy:* When members of an organisation share a vision and pursue it strongly it becomes an ideological strategy. 4. *Umbrella strategy:* When leaders only have partial control over actors in an organisation, they implement a vision but have to convince others to pursue it. 5. *Process strategy:* Leaders exercise influence on strategy indirectly, for example by controlling the staffing of the organisation, and thereby determining who gets to influence strategy. 6. *Unconnected strategy:* If a part of an organisation is loosely coupled to the rest, it might be able to realise its own pattern in its stream of action and therefore its own strategy. 7. *Consensus strategy:* No need for central direction or control is required since different actors naturally converge on the same theme so it becomes pervasive in the organisation. 8. *Imposed strategy:* The organisation is forced into a pattern in its stream of actions of the environment, regardless of the presence of central control.

CASE STUDY

Company A has a total of eleven employees in the design department, divided into the functionalities of Design Process Manager, Purchase, Structural designers (six persons), Electrical drafting and HVAC drafting (two persons), see figure 1. A role called early planning has been established to enhance the readiness level of the input from the sales department to the design team. Sub-contractors are utilised for static calculations, foundation drafting and ventilation drafting.

Company B has a total of seven employees in the design department, divided into the functionalities of Design Process Manager, Project Manager, Design Manager, Purchase, Coordinator for sub-contractors, Building design and Structural design, see figure. 2. Sub-contractors are utilised for HVAC, foundation and ventilation drafting.

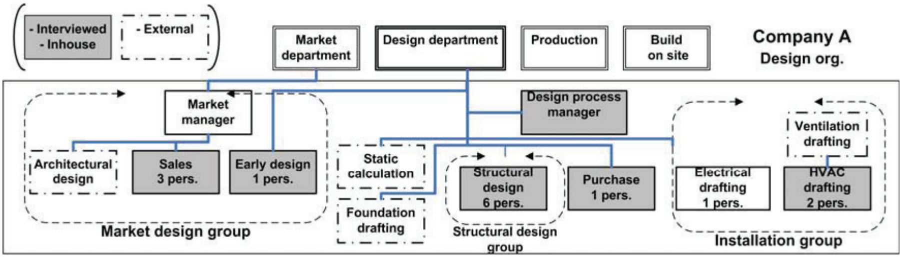

Figure 1. Company A organisation chart.

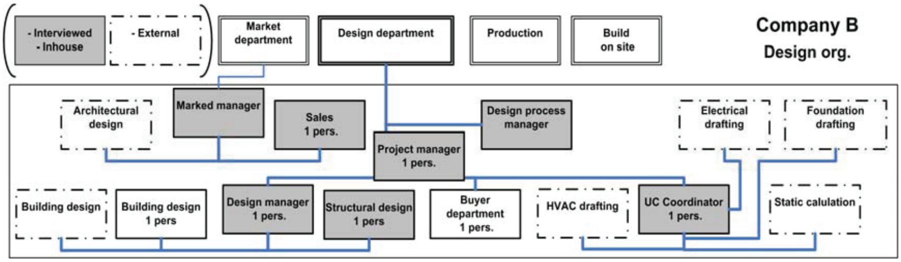

Figure 2. Company B organisation chart.

Company A works project-based with normally just one project simultaneously, but occasionally two projects have been processed in parallel, see figure 3. At Company A, planning of projects is based on time in total for the entire group. The Design Process Manager distributes tasks and assignments to the members of the team, which they work with throughout the project.

Company B has a clear process-based approach with a capacity of up to six projects in parallel, see figure 3. Due to parallel project, Company B plans every included part of the design process in detail. Every team member can be described as a specialist within a certain area i.e. 2D CAD-drawing, design managing, volume construction.

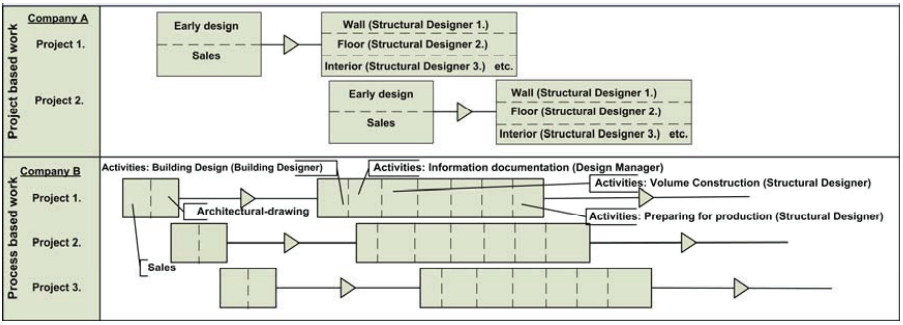

Figure 3. Design process illustrated in project and process based work.

Planned time for the design process has in both companies a mean value of 20 weeks from the start-up meeting to the production start. Both companies strive to reduce the design process time by 50 %. Company A is planning to reinvest the reduced time in standardisation of the building system, whereas Company B has an intention to focus on enhancing quality throughout the entire process. Activities are carried out sequentially as in traditional site construction for both companies, with documents being the most central information carrier instead of information systems. Company A uses one 3D-CAD software in which all design and drafting are performed, while

Company B uses several software and is therefore obliged to produce up to four different model files.

For visualisation of the design process, both companies use visual planning. Company A uses live documents on a file server with ongoing projects' status, while Company B uses a whiteboard where the current status of thirty-two activities/documents is indicated by different colours.

Company A has recently decided to apply lean principles to the entire company, starting with enhancing the design process and plan to work their way throughout the production flow. Company B has focused on improving the production capacity by investing in automation of the wall production line and has no comprehensive strategy for improving the design process. Lean principles are only used in minor sections in the design process at Company B.

ANALYSIS

Analysis of the design process at the two companies was done based on the lean perspective criteria in column 3, table 1. The analysis gives an indication on how well the design processes correspond to lean principles. Numbers in brackets indicate the corresponding criterion in table 1.

Value: Company A has their focus on the product in an object-oriented organisation. Value for the customer is the possibility of having better quality and controlled technical solutions due to an individual owner for each task in the design process. Customer value is a pronounced focus at Company B where the strategy is to take market shares in a new market area. The process-oriented organisation creates value for the customer, through flexibility in handling parallel projects in the design process (1.1, 1.2). Weekly meetings and sharing of visual information creates value for the design team itself. Waste is identified in the communication with sub-contractors e.g. time delays for checking drawings, information about project specific conditions and drafting revisions (1.3, 1.4)

Value stream: The value stream can be defined in resources and activities for conversion in Lean Design, where Company A uses fewer interfaces in the process but more interfaces in the product e.g. between wall and openings, wall blocks and inner roof. Company B has to deal with many interfaces in the process, to promote the value stream, such as software file formats, individual task status and individual work standards, but remains a comprehensive view on the whole product. Standardisation in the design process is done on a deeper level for Company A with standardisation for tasks (2.1, 2.2, 2.3). Company B has maintained its process focus and has not put effort in the work of standardising sub-tasks.

Flow: The flow of information and drawings in the design process is low within both companies. Company A uses 3D-CAD with central models for projects but with limited connections to production compared to Company B. Up to four different CAD models can be produced for each project at Company B, which decreases the flow. The range of software is the result of the implementation of automated machinery in the production. Nail robots use control files created by the CAD-system (DDS), which increases the flow. Paper drawings are used at both companies (3.1). The use of sub-contractors in the design process sometimes causes time delays for information sharing. In-house resources can be seen as supporting flow (3.1, 3.2, 3.3, 3.4).

Pull: Production time is shorter than time for design, which fulfil the pull criteria in-house at both companies. However, overall rate in design is too slow, 20 weeks in average compared to 4 weeks of production in the factory. Company A has streamlined their design work to obtain a production with higher delivery accuracy. Company B on the other hand, has started with streamlining their production and is now taking measures to convert design to flow better (4.3, 4.4).

Perfection: By the use of visual planning both companies have transparency in their design process status. Templates, checklists and quality routines for following up projects are present, but not common in the design process (5.1, 5.2). However, the common goal for the design team is not perfection of the entire process, since sub-optimisation is common. Standardisation of certain sub-tasks is not the same as optimising the entire design process.

The analysis of the organisation in the two cases shows that the focus on different key factors for the entire manufacturing process affects the appearance of the activities and tasks in the design process. Company A’s approach of implementing early design and allocating personal component responsibility (e.g. walls and floors), creates an apparent project focus which generates value in the product, both for internal (production) and external customers. Company B’s strategy is reliant on customer requirements where the flexibility in the process-oriented organisation provides value for the customers. Having parallel design processes allows clients to influence the selection of components like alarm systems, kitchen appliances, etc. further into the design process. Decisions have to be structured with several object-specific deadlines through the process to use the advantage of flexibility.

Company A is part of a larger corporation where strategically important decisions and directives are emanated from central leadership. Therefore the concept of planned strategy, according to Mintzberg and Waters (1985), appears to be the best comparable alternative. According to Liker (2004) there is an evident need for leaders to live the philosophy of Lean and spread it to employee (top-down implementation). Company A has recently decided to adopt lean principles on the company.

Company B is a family business with a strong leader and facilitating Mintzberg and Waters (1985) terminology, the concept of entrepreneurial strategy seems to apply the best.

Since the leader’s vision is personal, it can also be changed completely. This allows the organisation to quickly respond to changes in the environment, thus can be considered to enable implementation of new strategies. Company B has not adopted lean principles at a company level, but there are actors in the organisation influenced of Lean Thinking. Based on the evaluation of strategy types, neither of the companies appears to have strategies especially facilitating or obstructing implementation of a lean concept.

Standardisation is a principal strategy to create efficiency in the design process and the authors perceive different conditions at the studied cases. Company A have clearly defined their organisation with distinct assignments and responsibilities. Implementing the function of early design has given Company A the ability to ensure that potential projects are compatible with the building system as well as enhancing the quality of data entering the design process.

Company B has an organisation with explicit responsibilities, but activities are not divided into assignments for specific persons. The process-oriented approach creates expertise in performing the work task, but may not contribute to improvement of the product since focus is placed merely on one activity. Working with several different

ICT tools, results in a non favourable situation regarding managing versions of files and documents. Based on these findings the authors believe that standardisation of the building system might be more straightforward to execute at Company A.

Using lean production principles to improve the design process in industrialised housing is considered to be insufficient due to the complex situation of being manufacturers in a constructional context. Neither concepts nor theories founded in manufacturing settings or traditional site construction are completely valid for these particular circumstances. Lean production is by Crowley (1998) described as "unsuitable to small-scale production of non-standardise or customised products".

Jørgensen (2006) states that defining value for end customer in construction is complicated since end customer for a building can be several different individuals distributed over extensive periods of time. Furthermore, it cannot be taken for granted that an increased productivity necessarily serve the interests of the end customer (Green 1999). Neither can flow be considered to be as essential in everyday work as in theory, since the design process is not sequential as production generally is.

In order to differentiate which activities being repetitive (and beneficial for standardisation, i.e. cross sections, fire documentation and room description) from project-unique activities ("handled individually", i.e. balcony solutions, elevator and stairwell) the design process must be fractionised and analysed.

Former research in this field has primarily discussed the influence of lean production on regular site construction (Green 1999; Naim 2003). Since Koskela (1992) introduced Lean Construction, focus has shifted towards investigation of its applicability (also on site construction). Therefore it has been of extra interest to perform this case study with lean production perspective in the industrialised housing context.

This study states that lean production alone, is not a sufficient tool when improving the design process in industrialised housing. Future work needs to combine lean production and lean construction to support industrialised housing.

CONCLUSIONS

Industrial housing companies have to acquire control over the process to benefit fully from owning the entire system and therefore being able to improve it. Using only lean production principles for improving the design process is not sufficient.

It is therefore needed for the industrialised timber housing companies to:

- Thoroughly investigate all included tasks within the design process in order to differentiate repetitive and project-unique activities. By doing this, tasks suitable for standardisation can be identified.
- Standardise procedures for repetitive work in order to better utilise resources as well as ensuring that knowledge of the product and the building system is captured within the system itself, not only in persons working in it.
- Make use of well-suited ICT support to automate interfaces. Industrialised housebuilders have reoccurring interfaces every time the design process is repeated. However, they may not necessarily have a repetitive design in itself.

ACKNOWLEDGEMENTS

For assistance in data collection the authors would like to thank Sara Holmgren. This work was performed within the competence centre Lean Wood Engineering.

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PAPER II

Platform use in systems building

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Special issue of Industrialised building in Journal of Construction Management and Economics in May 2013

Construction Management and Economics, 2013
http://dx.doi.org/10.1080/01446193.2013.793376

Platform use in systems building

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Received 29 October 2012; accepted 1 April 2013

The practice of reusing processes and technical solutions leads to the formation of product platforms in house building. Product platforms originate from industries employing a make-to-order production strategy, e.g. the automotive industry. To test how the product platform concept is useful in engineer-to-order production strategies, a case study at two Swedish house-builders was made. Key factors that affect platform use in systems buildings were sought. The smaller company operates a supplier-led platform focusing on commonalities in process knowledge. There is less definition of the product itself to allow for distinctiveness in the product offer. The larger company has a decentralized business and operates a client-driven platform with fragmented standardization. Focus is put on creating commonality through defining the product and handling distinctiveness through an iterative design procedure. Product families were not in use at the case study companies. The companies transform standardized platform solutions into project uniqueness by using support methods. Four platform support methods emerged from the case studies: design planning, collaborative design, design optimization, and requirements iteration. The balance between commonality and distinctiveness in the platform is important to attend to in each house-building project. The engineer-to-order production strategy hinders the implementation of a fully parameterized platform. The product platform concept is therefore expanded with support methods to handle distinctiveness, i.e. project uniqueness. The product platform assets: components, processes, relationships and knowledge, are present also in platforms used in systems building.

Keywords: Case study, design, industrialized building, product platforms, support methods.

Introduction

The Swedish housing sector has seen a strong development of systems building stemming from the long tradition of industrialized production of single-family houses (Samuelsson, 2001). Prefabrication with systematization of processes and components was the foundation in systems building during the industrialization of housing in the middle of the twentieth century (Finnimore, 1989). Current demands for shorter lead times, customized buildings, and quality of deliveries compel construction firms to systemize work in their own supply chain. The design phase is today a critical part of construction with high demands on timely and exact deliveries produced over the shortest time period possible.

Construction design in general suffers from inefficiency in deliveries where time, cost and quality are not consistent with contracts (Tilley, 2005). To balance the focus on the project uniqueness with the economies of scale created by standardization is a challenge. The purpose of managing design efficiently in housing is to generate the benefits of project repetitiveness without limiting the distinctiveness of client choices (Thuesen and Hvam, 2011).

Construction is identified as one of the largest engineer-to-order (ETO) sectors (Gosling and Naim, 2009). In an ETO context, the client enters the supply chain somewhere during the engineering phase (see Figure 1), enabling the client to affect the output, i.e. to customize the final solution. The engineer-to-order supply involves a non-physical stage that includes tendering, engineering and process planning activities, as well as a physical stage that comprises component manufacturing, assembly and installation (Sackett *et al.*, 1997).

With ETO in general, the product structure is deep and complex (more than six levels), which

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*Author for correspondence. E-mail: Gustav.Jansson@Ltu.Se leads to a supply chain with many levels that tends to be unstable between projects (Bertrand and Muntslag, 1993). Systems building as a part of house-building can be interpreted as a predefinition of the engineering phase (see Figure 1), and leading to a predictable and stable supply chain. A stable supply chain enables the use of design management strategies (adapted from product development theories) with the goal to standardize technology and work processes (Jiao *et al.*, 2007a). In systems building, the supplier addresses this situation by forming a product platform. A product platform is an integral part of the value chain in a company (Robertson and Ulrich, 1998; Sawhney, 1998).

Robertson and Ulrich's (1998) definition of a product platform, containing the assets *components, processes, knowledge* and *relationships* is further developed and analysed in this research. Product development methods presented by Robertson and Ulrich (1998), and Meyer and Lehnerd (1997) are based on product platforms organized for large series production, using a make-to-order strategy (or those below in Figure 1). For house-building where the ETO strategy is used, one has to manage and repeatedly apply platforms in a series of projects in combination with unique client orders. The interface with the client is therefore of utmost importance.

Even though knowledge, rules and standards are stored in projects and people, Styhre and Gluch (2010) recognized the challenge of using platforms in their study of a Scandinavian construction company:

> … platforms are not very easily implemented in the construction industry since there is a strong instituted principle in the construction industry to avoid standardized solutions and off-the-shelf design of buildings. (Styhre and Gluch, 2010, p. 590)

By reusing solutions in sequential house projects, experience from design and production is gradually stored in the platform for future use (Robertson and Ulrich, 1998). The product platform is applied in the design phase, which makes engineering a crucial activity in confining the platform and preventing project-based development of new variants (Jiao *et al.*, 2007a). Different support methods, e.g. collaborative design (Senescu *et al.*, 2013), are used in housing design to manage a platform on a daily basis. The support methods can emphasize different platform assets, i.e. collaborative design supports knowledge and relationships, but does not build process knowledge.

As an indicator of the development and use of housing platforms, Thuesen and Hvam (2011) presented quality and lead time improvements as well as a reduction of project costs by 30% in a study of a German housing platform. The study embraced one platform on a 14-year base and would need further confirmation.

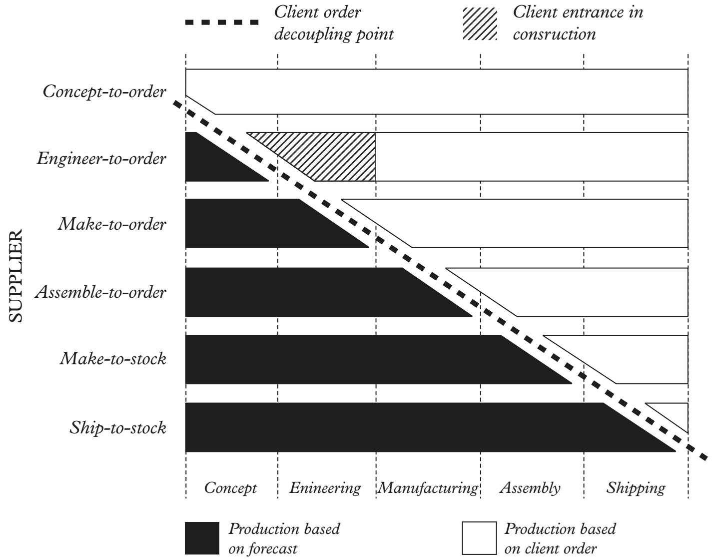

Figure 1 Visualization of the decoupling point between supplier and client (revised from Sackett *et al.*, 1997)

Because of the strong instituted principles in construction, it is important to study methods to support the use of a platform. Furthermore, the ETO situation would imply that there is a possibility for variation between systems building platforms in both the degree of predefinition and the focus in the supply chain. It is crucial to understand how the interaction between the application of support methods and the platform affects platform use in an ETO situation for systems building.

The aim is to understand and develop the product platform concept for the ETO situation exemplified by systems building, and to identify key factors that affect the use of platforms by analysing support methods and their application to platforms in daily engineering work.

Systems building using product platforms

Platforms

Robertson and Ulrich (1998) present a platform planning strategy, based on observations of the car industry, with design methods that balance customer needs with production costs. They define a product platform as follows:

> A product platform is the collection of assets [i.e. components, processes, knowledge, people and relationships] that are shared by a set of products. (Robertson and Ulrich, 1998, p. 3)

Following the line of the above definition, the platform affects product development, production and logistics processes, organizational structures and knowledge within the company managing the platform (Muffatto and Roveda, 2000). Meyer and Lehnerd (1997) supported the idea that the platform consists not only of physical parts, but also of process technologies and organizational capabilities.

By studying Black & Decker's and Hewlett Packard's product development in product platforms, Meyer and Lehnerd (1997) presented the Power Tower model (Figure 2) with the elements of: market instantiation by product families, product platforms nurturing several product families and the four basic assets serving as building blocks within a platform.

Platform assets

For large series of products, *components* are key elements while in the ETO context (e.g. construction or software business) component interfaces are central for project configurations (Thuesen and Hvam, 2011) and therefore the platform concept needs adaptation to specific contexts. *Components* are the physical building blocks used when designing a product and the related tools with manufacturing fixtures (Robertson and Ulrich, 1998). A focal point in Robertson and Ulrich's (1998) platform planning is the balance between *commonality* and *distinctiveness. Commonality* is the common base in the platform and the driver for simplicity and cost. Common parts

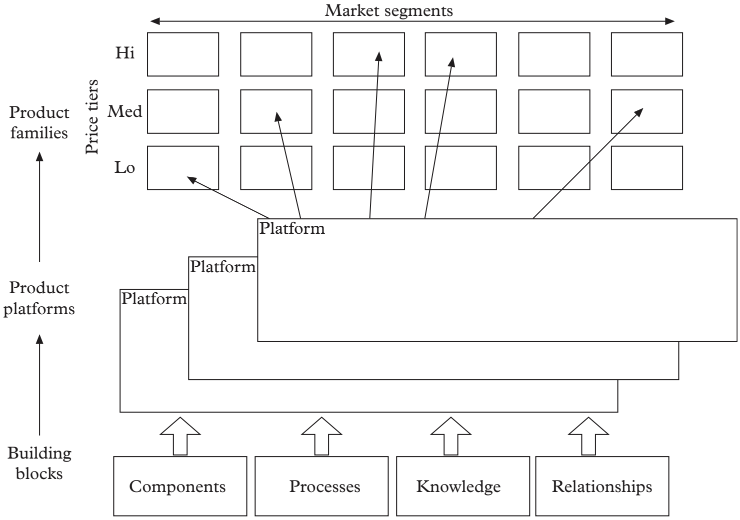

Figure 2 The Power Tower model of a platform (Meyer and Lehnerd, 1997)

appear in every product model produced within the platform. From a client point of view, the commonality in a platform provides no variation between models. When adding *distinctiveness*, the individual product uniqueness is created. To produce customized products efficiently, knowledge about production processes are gathered and refined to form the *process* asset of a platform. Process assets have a generic structure from which variations in diverse products and processes can be differentiated (Jiao *et al.*, 2007b).

According to Styhre and Gluch (2010), the *knowledge* asset is a mechanism for bridging between the stocks and flows of knowledge in construction organizations by integrating know-how and experience in activities. Knowledge sharing is a complex process and is practised in construction mostly by local networks and oral communication (ibid.).

Relationships initially concern people working on platform organization for product development. These people are organized in cross-functional teams with the task to either develop product families or to diffuse common solutions throughout the whole range of products (Muffatto and Roveda, 2000). Also relationships concern the relationships with other companies in the supply chain, where some actors are more closely coupled to the platform than others (Green *et al.*, 2005).

Support methods for platform use

Simpson *et al.* (2006) and Jiao *et al.* (2007a) further developed the product platform concept by adding methods for planning, decisions, optimization and configuration to support the engineering work. Their methods were found through summarizing literature in the field of product family development, and are used both for platform development and for configuration of product families to balance between client needs at the *front-end* of the supply chain and production costs at the *back-end* (see Figure 3).

The model for platform development incorporates iterations through the design of the product, the production process and the supply chain, based on axiomatic design theories (Suh, 2001), Figure 3. A predefined solution of these process steps forms a platform (ibid.), which is illustrated by Jiao *et al.* (2007a) in Figure 3: the predefined parts (the platform) are hatched (Jensen *et al.*, 2012).

Customization, configuration, production, supply and assembly are all activities in the process of defining the product that are supported by the platform. Research on applications that support the development of product families has been focused on configuration, e.g. agent-based or knowledge-based schemes for *back-end* decisions about manufacturing, production and logistics (Jiao *et al.*, 2007a). The front-end perspective focuses on innovation, higher performance, and lowering of client costs (Simpson *et al.*, 2006). Jiao *et al.* (2007a) argued that extended configure-to-order platforms (instantiated by guiding the client through a decision framework) could capture front-end issues and align them with back-end issues for product customization. Configure-to-order platforms are either ETO with a high degree of pre-engineering or make-to-order with a configuration process during sales. The platform development strategy is not successful in general; instead it requires the company to develop standardization for specific markets (Muffatto and Roveda, 2000). In housing construction there is a tradition of using different support methods for design in different projects and methods are often heuristic and chosen by project managers or by the design group.

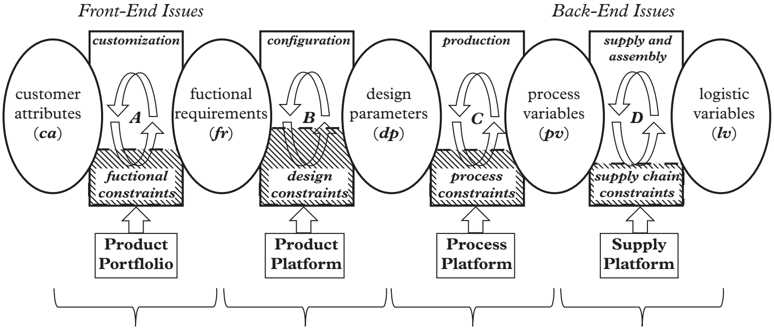

Figure 3 A holistic view of product family design and development (revised by Jensen *et al.*, 2012 from Jiao *et al.*, 2007a)

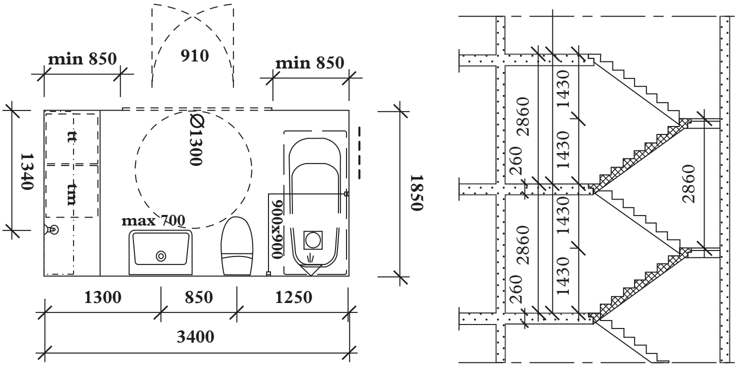

Figure 4 Data collected at the layout and detail levels, illustrating the component asset

The housing design context embraces communication within projects, sharing between projects, and knowledge generation across entire firms (Senescu *et al.*, 2013). When working as an engineer within a platform, your task is not to optimize the engineering work only, but also to balance your solutions for the success of the entire platform. Normally, this results in solutions that are non-optimal within a certain discipline, but the best possible for the performance of the platform. In Thuesen and Hvam's (2011) study of a platform for house-building in Germany, flow-based activity planning, combined experience/loyalty to standards, requirements handling, and value configuration were used as support methods to decrease costs and increase customer value from platform standards. The use of methods showed that a separation between platform development and use was needed to visualize the platform and to communicate internal trust in project implementation.

Design work in systems building

Design in systems building means transforming unique client-specific needs into houses that can be efficiently manufactured. By describing the relevant processes, according to a product range and its variety, in interoperable information systems, Persson *et al.* (2009) argued that efficient design management by systemizing the work could reduce costs and increase productivity. Engineering work is a part of the design phase where the platforms are configured to meet project variables. In a study of a Scandinavian contractor Styhre and Gluch (2010) recognize the platform as a tool of boundary objects that serves engineers with know-how, experience and other resources for effective work for the whole supply chain. The boundary objects (in instructions, blueprints, recommendations, etc.) should also allow local variations and individual creativity. Styhre and Gluch (2010) recognized that knowledge had the function to act as a bridge between accuracy and flexibility when combining the companies' boundary objects.

To improve housing design, discrete changes in technology and working practice can be part of the alignment between knowledge, capability, culture and management of control procedures (Roy *et al.*, 2005). In the context of construction projects, virtual design methods can be useful to manage components and technical solutions and to obtain pay-off from the repetitiveness in the product offer (Ekholm and Molnár, 2009). In systems building, when making a wholesale process commitment, design must manage not just the technical competence but also cooperative capabilities such as knowledge transfer, the ability to develop trust and meaningful negotiation, competencies in information processing, communication and intra- and inter-unit coordination (Johnsson and Andreasson, 2013).

Method

From the context of systems building and earlier studies of platform application in housing, the question of whether platforms can be straightforwardly applied to house-building was formulated. A literature study in engineering design and product platform theories in and outside the construction context formed a base for analysing the cases, i.e. the building design process at two different companies. The unit of analysis was the daily use of the platform through the application of support methods. By sorting the company activities in daily platform use and comparing them to platform theory, the conclusion was reached that the platform formulation suggested by Meyer and Lehnerd (1997) and developed by Robertson and

Ulrich (1998) did not really suffice in the ETO case. The adaptation to project-specific parameters was missing. This was achieved by the case companies through applying different support methods. From the results of the analysis platform key factors and a conceptual model for platform use in systems building were identified.

To understand the daily use of platforms in systems building, a study of two platform cases in construction was carried out: one case was an industrialized house-builder with offsite manufacturing (Company A) and the other, a large contractor (Company B) that works using industrialized methods. To create qualitative insights about platform use in housing design and identify factors governing the use of platforms, case study data were collected as a method of analysing qualitative phenomena (Miles and Huberman, 1994). Both Company A and Company B maintain control of the whole process. Two different organizations were chosen, not in order to create generalizability but rather to analyse the platform concept when it is applied to design from two different viewpoints. Company A is gradually opening up its platform for more customization, while Company B is in the process of finding its platform from a plethora of existing solutions.

Case study companies

Company A is an SME (small and medium sized enterprise) with an annual turnover of about €70 million per annum, active on the Swedish market, that has developed its platform to offer condominiums, rented dwellings, and senior housing based on prefabricated volumetric elements. The company was chosen for the study because of its use of a standardized product platform for housing where the design team has rigid requirements for fast and correct deliveries to an automated manufacturing line. Design management was studied over a five-year period with 52 projects providing input data. Interviews and observations were conducted over two time periods in 2008 and 2011.

Company B is one of the four largest contractors on the Swedish construction market with a turnover for housing of about €800 million per annum. Different product platforms are built up in order to support the entire company with standards for housing, infrastructure and commercial buildings. The company was chosen because the projects that are internally developed with wholesale process control have design support methods applied to them. Company B differs from Company A as it does not have any automated production in a factory, but constructs its buildings using traditional onsite production. The five projects studied at Company B generated findings about process, knowledge and relations in daily engineering work during the period 2011–12. The four support methods *design planning*, *collaborative design*, *design optimization* and *requirements iteration* emerged from the two case studies. These methods were used to analyse the support of platform engineering work in an ETO situation in order to find key factors for platform use in systems building.

Data collection

Quantitative data were gathered from documents, the business systems at the companies and the predefined rules expressed as templates in computer aided design (CAD) and customer relationship management (CRM) systems. In total, 1613 documents distributed in components (649) and processes (964 design, purchasing, and construction activities) were categorized from both companies. The knowledge base and the relations in the form of organized team set-ups and long-term contract formalization were gathered from a total of 62 documents.

By choosing semi-structured interviews to collect the contextual data at the companies, the respondents were able to freely describe their view of design support methods (Flick, 2009). The interviews validated quantitative data collected in the form of written platform documentation. During interviews with respondents at the companies, the central documents and standards for the product platform, along with instructions for platform use, were identified and described. At Company A, interviews were carried out on an operational level with two project managers and two structural engineers. Because design and prefabrication are centralized, with short internal communication paths, interview questions were asked about operational engineering work and related methods that support platform use.

Eight interviews were planned and carried out at Company B with both strategic (two platform managers, two business managers) and operational staff (two project managers, two structural engineers) in order to capture platform use from a wide point of view. To verify data sources (Miles and Huberman, 1994) and obtain a clear picture of company design work from a platform perspective, two method developers and two additional operational project managers were interviewed after data analyses of the documents. All interviews at both companies had guiding questions followed by open-ended questions to allow the respondent to describe the platform topic from different perspectives (Miles and Huberman, 1994). The purpose of this structure was to capture platform granulation and understand the focus of support methods in relation to the data collected from the documents.

Analysis

Platform assets and support methods for design in systems building were analysed to identify factors and understand platform use in an ETO situation. The data about the platforms were grouped by the first author into components, processes, knowledge and relationships in order to identify the level of commonality and focus within the platforms. The results are shown in Tables 1 and 2 with calculation of the percentage of commonalities for the component and process assets in the building projects studied. This is illustrated in Figure 5, where the hatched area indicates commonalities for a particular asset. The engineering support methods were also analysed to categorize them (Miles and Huberman, 1994) as supporting flow and/or client orientation in Tables 3 and 4. Finally, how the support methods focused on front-end or back-end issues was analysed using the theory of platform use (see Figure 3). Here it was discovered that the actual existence of support methods in design violates the platform concept as visualized by Meyer and Lehnerd (1997). Therefore, a tentative model, Figure 6, was suggested as valid for the ETO situation where support methods are used as a means to produce distinctiveness instead of the product family concept.

Case study results

Both companies are in a phase of development of their systems for a specific supply chain, using different organizational resources but describing the same goals: to meet client needs with profitable production. The companies have captured their platforms in documentation that describes commonalities for components (technical systems) and processes (design, manufacturing, supply chain). Unique solutions for client customization are managed in the engineering phase by either applying a platform option or developing a new solution that fits the platform. Company A has a clear focus on the structural system

Table 1 Distribution of component standardization in platform documentation

Predefined components	Structural framework	Windows & doors	Balconies & façades	Room specification	Corridors & stairwell	HVAC & plumbing	Electricity	Roof structure	Groundworks & foundation
Company A	134 (47%)	36 (13%)	22 (8%)	56 (20%)	11 (4%)	10 (4%)	3 (1%)	11 (4%)	0 (0%)
Company B	46 (12%)	27 (7%)	29 (8%)	93 (24%)	13 (3%)	49 (13%)	88 (23%)	21 (6%)	17 (4%)

Table 2 Distribution of process standardization in platform documentation

Predefined activities	Design	Purchasing	Offsite production	Onsite production
Company A	187 (33%)	98 (17%)	115 (20%)	171 (30%)
Company B	251 (63%)	49 (12%)	0 (0%)	98 (25%)

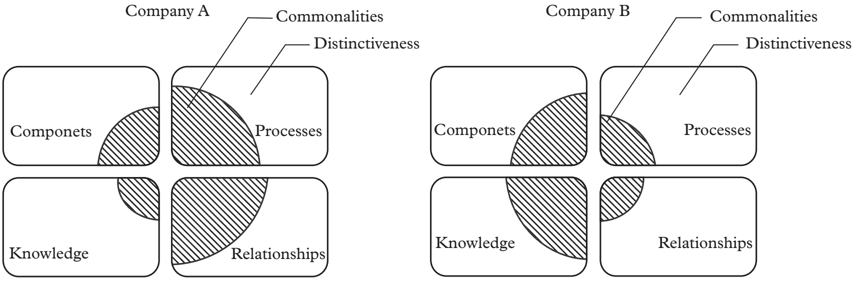

Figure 5 Distribution of platform documentation

in the platform with a few rigidly defined component/system commonalities (see Table 1). Furthermore, some spaces are standardized in the floor plans, e.g. bathrooms and student accommodation spaces. Company B has distributed its documentation of the platform standard more evenly across the four constituent parts of the platform (Robertson and Ulrich, 1998). However, Company B emphasizes room descriptions and heating, ventilation, and air conditioning (HVAC) solutions based on CAD models and written documentation, with a high level of detail on how to create production deliverables.

By combining product and process standardization on how components, technical sub-systems and systems should be produced, both companies have standardized their work to differing degrees with a clear strategy of achieving productivity. Company A, using a higher proportion of offsite manufacturing, has defined work tasks down to component level, complete with work routines for offsite production. Company B has defined its processes as activities and routines, both in its business system and in written procedures. Neither of the two case companies has documented all their design and production activities. Onsite standardized work is less documented in comparison to offsite and design work at both companies.

Knowledge about both technical systems and processes is documented in Company B and is stored in its enterprise resource planning (ERP) system in order to achieve transparency between building projects. Company A has documented its knowledge base in routines together with product and process standards, but does not make use of an ERP system. The experience feedback in daily work updates production knowledge which in turn provides feedback to the engineering phase. The experience feedback is documented but is less analysed (Johnsson and Meiling, 2009).

Long-term contracts with suppliers and subcontractors have been set up by Company A to help it predict the flow and increase precision for the whole supply chain. Three defined design teams manage between six and nine projects in parallel, to feed the factory with deliveries in the form of drawings, descriptions and data. The speed of the engineering phase for Company A is planned according to a fixed production flow in the factory. Company B, which does not have a factory, strives to keep the same set-up of participants through the design phase. In spite of this, in Company B changes of actors often occur because of long cycle times. Typically 25–50 weeks are spent in the engineering phase for the case study projects. The design teams in Company B frequently use multidisciplinary interaction in the later part of the engineering work. Company B separates product and process standardization in its platform and has more documented routines in the engineering phase to control its organization than Company A. Company B has no long-term contracts with suppliers, but procures them for every project.

For both companies, undefined distinctiveness is a major part of their platforms, which then has to be managed in the design phase. Some variants creating distinctiveness are defined for components but fewer or none describe process, knowledge, and relation distinctiveness.

Support methods for platforms

Construction design has become more fragmented with specialization and this puts demands on the *design planning* to manage both the business and project domains. Planning is carried out from a pull-perspective at Company A where a lean production approach is under implementation. The production flow in the factory affects the pace of engineering work and therefore the design activities and deliverables have been deconstructed in a work breakdown structure (WBS) with the associated delivery times. The delivery times are checked at daily meetings. This has led to an increase in engineering work speed with a nominal average time frame of 16 weeks per project.

Company B, which offers a wider range of structural solutions than Company A uses a more traditional construction engineering work method combined with visual support methods. Owing to the long-term deadlines (often 6–12 months for the engineering phase) and the use of a site-based production set-up, time planning uses tolerances.

Collaborative design is used to match the speed between production and engineering in Company A and is applied in all projects. The design team meets on a daily basis, checking and adjusting the deliverables following the set time plan. The time plan has been broken down to identify commonalities in the platform based on activities in the engineering phase. This forms the base in design planning and provides a common language for succeeding with collaborative design.

Collaborative design at Company B is used to validate deliveries and ensure constructability. The design team meets weekly in a special design room using a set agenda to discover, analyse and monitor project problems. Much of the work revolves around virtual models displayed during the meeting as a base for discussion. The design time is not substantially reduced but according to interviews, more problems are solved before production using *collaborative design*.

Design optimization is used by both companies to store and communicate continuous improvement and client satisfaction through knowledge that is highly critical to the companies' survival. Company A has an operational approach through daily feedback where deviations are reported and handled to increase quality in deliveries within its platform but also to continuously improve it. The overall idea is that the feedback reports should be analysed and changes implemented to the engineering work process. This is only partially functioning, since the engineers receive many feedback reports and they state that there is no time to incorporate all of them. Company B uses central expertise to streamline and optimize the use of platform standardization with a focus on components. This optimization follows a defined plan, which is followed up later in the design phase. The experts continuously define and develop the platform from experience and knowledge derived from audit data and production costs.

Requirements iteration is practised at Company B in some projects where experts on energy usage, acoustics and fire are invited early on in the engineering phase in order for the company to make use of positive iteration for technical solutions that adhere to platform standards. Requirements iteration is an inseparable part of design in the various phases of construction projects where the engineering work is done by iterating drafts until the design parameters for different systems are locked. The use of requirements iteration in the platform is related to the management of commonalities for solutions like ventilation systems, balcony solutions and plumbing systems. Company A also uses technical expertise in areas such as structural engineering, energy usage, acoustics and fire but only in the later phases of engineering; it relies on rules in the standardized platform for early design. According to the project managers, no requirements iteration is performed at Company A unless the manufacturability of the platform is violated.

Analysis

Analysis of support methods

The support methods were chosen to support design work at both case study companies. Tables 3 and 4 describe how the four support methods focus on different platform assets at Company A and Company B. A stronger focus by using a method on a particular asset results in darker shading; lighter shading indicates weaker focus.

The support methods employed at Company A have a clear back-end focus on production and supply chain issues using the method *design planning*, which combines resources from the design and production phases. The use of routine processes gives opportunities for speed in the process (Jiao *et al.*, 2007b) where Company A, through its coherency in organization, has developed connections from general processes down to task level. The back-end focus is also shown in the *collaborative design* where platform commonalities in engineering activities enable a faster flow through the design. Company A bases its *design optimization* on platform performance feedback which is used as a project input at the beginning of the design process. It relies very little on methods that invite the client to follow the process, e.g. *requirements iteration*. This indicates a lower client focus in the design process at Company A than in Company B.

Company B has developed a front-end focus on client requirements using *collaborative design*, inviting the client to participate in the process. *Requirements iteration* is practised at Company B, where the method supports matching platform-based solutions to project requirements. Focus is put on technical solutions

Table 3 How the support methods in design focus on the platform assets at Company A

Company A	Design planning Back-end focus on planning the process	Collaborative design Back-end focus on planning the process	Design optimization Back-end focus on feedback to optimize process	Requirements iteration
Component	Parts delivery scheduling	Securing manufacturability	Daily feedback reports and documentation	Not practised
Process	Detailed activities and deliveries plan	Daily meetings, flow-oriented	Daily feedback with platform improvements	Not practised
Knowledge	Pull-based project dependent planning	Activities sorted in commonalities and distinctiveness	Continuous improvements separate from the design process in projects	Not practised
Relationships	Long-term, fixed relations	Fixed relations and predefined deliveries	Operational feedback on behaviour and deliveries	Not practised

Table 4 How the support methods in design focus on the platform assets at Company B

Company B	Design planning Back-end focus to find correct solution	Collaborative design Front-end focus to solve client problem	Design optimization Back-end for component, front-end for knowledge	Requirements iteration Front-end focusing component requirements
Component	No focus	Model-based clash detection	Centralized hierarchical documents	Functional requirements to design parameters
Process	Sub-process planning, deliveries plan	Weekly meetings, quality-oriented	Discrete events, reflection twice in every project	Iterations of requirements through design
Knowledge	Push-based project planning	Problem solving by technical experts	Centralized documents issued in versions	Early expert involvement
Relationships	Varying relations between projects	Project organization, unstable over time	Feedback from strategic level	Client, suppliers and technical experts

(components), which are designed using client requirement input. *Design optimization* together with *design planning* have a back-end focus on cost, planning and commonalities in components, containing tested knowledge and organized to increase the use and development of the platform.

Collaborative design, *requirements iteration* and *design optimization* are methods that not only tailor the specific platform assets to project parameters but also manage the transformation of the client demands in the front-end to the production and supply chain in the back-end of the building process. Applying support methods can emphasize different assets in the platform. *Design planning* supports drafting deliveries and documentation of processes while *requirements iteration* supports the gradual discovery of an answer. To define platform rules in construction, the identification of commonalities requires combining design and manufacturing processes for components (Thuesen and Hvam, 2011).

Platform use in the ETO situation

The support methods applied by the case study companies are meant to support the daily use of the platform. These are currently not part of the theoretical description of a platform (Robertson and Ulrich, 1998; Simpson *et al.*, 2006). Platform use in an ETO context must allow for project commonality and distinctiveness, given the project organization and its inherent content of a mix between standard and customized solutions (Roy *et al.*, 2005). Because the context is ETO without the use of fully predefined products, the platform assets are not defined in product families before an order, which contradicts Meyer and Lehnerd's (1997) view of platform organization. Each project replaces the use of product families.

The engineering support methods have to support the use of defined commonalities and yet allow creative design for both onsite and offsite construction. The support methods are used to bridge the gap between the standardized platform and the project-specific parameters. As an example of bridging, some component blocks are standardized as commonalities in the platform, so Company A uses timber-framed modules and Company B standardizes storey heights and floor spans. Both technical systems rely on engineering to match these commonalities to a project's unique site layout and building footprint by the use of support methods.

As a tentative model for the function of platforms in the ETO situation, the structure shown in Figure 6 is proposed. The product platform in Figure 6 is based on the same four assets *components*, *processes*, *knowledge* and *relationships* as defined by Robertson and Ulrich (1998). Predefined commonalities for each of the four assets are stored within the platform, i.e. components and activities from Tables 1 and 2. Instead of combining commonality and distinctiveness parts into product families, support methods are used to combine platform commonalities with project distinctiveness (Figure 6). The distinctiveness parts of the platform are not fully predefined, but can be affected by the client during the design process and are handled by the support methods so as not to violate platform use.

In essence, Figure 6 is a variation of the original platform definition by Meyer and Lehnherd (1997) and Robertson and Ulrich (1998).

In an ETO context, the knowledge of the product itself needs to be complemented with structured knowledge, i.e. the process and knowledge assets, on how to develop project dependent variations that still remain inside the platform, thus not compromising downstream efficiency. As shown in Tables 3 and 4, both companies are knowledgeable in support methods. Tentatively, platforms used in an ETO context

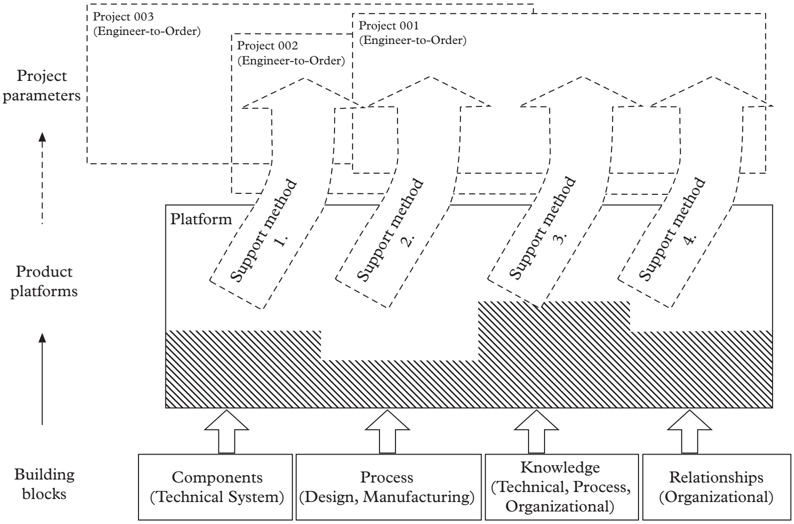

Figure 6 Proposed platform model for an engineer-to-order supply chain

would need a stronger focus on knowledge than found in a make-to-order context.

The two companies differ on one interesting point. Company A has integrated the supply chain and therefore has a stronger focus on processes that are connected to components in its platform. Company B, on the other hand, works with (the more common) fragmented construction supply chain, procuring subcontractors for each new project. Company B therefore has a stronger focus on the product, since the process knowledge downstream is somewhat out of its control. Company B has instead focused on front-end issues and uses *requirements iteration* in the early design phase. Company A has higher predefinition in its platform and has chosen to skip practising *requirements iteration*.

Company A has concentrated standards in its platform focusing on the structural elements used in factory production and support methods that address *back-end issues*. Company B has a fragmented platform approach with support methods and platform standards for both *front-end* and *back-end issues*. A similarity between the two companies is the focus on the documented platform standardization and support methods, but on different assets (components and knowledge for Company B; processes and relationships for Company A). Both companies leave the engineers unsupported in some parts of the design process. By allowing engineers to solve client requirements (front-end) without support methods there is a risk that unique project-specific variations in the platform may slowly cause it to degrade (Senescu *et al.*, 2013).

In both companies, platform development is an ongoing process and support methods could be complemented by standards within the platform for more defined products for specific markets. Since the development of platforms is rigidly connected to the daily engineering work in a project organization, the separation into pure platform development is needed to control investments and progression Thuesen and Hvam (2011).

Discussion

Engineering work in housing design makes the client a natural part of the design process––a more gradual decoupling point than visualized in Figure 1. The platform constitutes what the supplier must adhere to, to complete production. Hence client requirements are drivers for the unique parts of the platform and all platforms in construction need a unique part, due to the decoupling point.

The ETO context with changing client demands hinders a fully parameterized platform. From the cases studied, support methods are used by suppliers to handle the distinctiveness in partly defined platforms. The choice of support methods would be an area that needs further study and development. The importance of choosing a certain support method is unknown.

Company A has chosen to document its design process in segmented standards for offsite production and manages a supplier-led platform focusing on back-end issues and is constrained from opening up production for a wider market. There is a risk of engineering work taking over the focus on client needs. In a situation where employees enter the company, having component and knowledge assets undefined would lead to a slower uptake of platform knowledge, thus leading to a decrease in efficiency.

Company B on the other hand operates a client-driven platform which is able to solve front-end issues and is thus able to address different market segments but pays through longer lead times caused by back-end issues (Jiao *et al.*, 2007a), with fewer documented processes and relationships. A fragmented, partly standardized platform does not yield economies of scale because of the lack of connection between component and process standardization (Simpson *et al.*, 2006). In the ETO situation with a gradual decoupling point, knowledge about client needs becomes essential for planning engineering work and realizing the possibilities to configure platforms that match the production and supply chain for each housing project. In platform planning in systems building, choosing *how* to standardize (focus on specific parts, e.g. the structural frame or work across the entire supply chain simultaneously) should have the highest priority. The case study result showed that interfaces between platform assets are difficult to define, where isolation of standardization resulted at both companies.

Conclusions

Design support methods for daily engineering work are needed when using platforms in an ETO context in order to bridge gaps between project requirements and platform parameters. Meyer and Lehnerd's (1997) model of a platform (Figure 2) cannot be applied straightforwardly by ETO companies but needs to be amended with a project-specific part with related support methods, to be able to maintain platform core values (Figure 6).

Separation between platform development and platform use is difficult in an ETO context even in systems building. Although it is possible to carry out product development outside projects, it is not always feasible since not all client needs are predictable, but arise when project requirements meet platform parameters in the engineering phase. From the case studies and the analysis, *platform assets*, *categorization*, *distribution* and *focus* are key factors describing a platform:

- The platforms used in systems building have been shown to contain the assets of components, processes, knowledge and relationships as proposed by Robertson and Ulrich (1998).
- Commonalities and distinctiveness are useful categories in platforms for ETO, regardless of technical systems and the supply chain structure.
- Product families are not a useful category for all systems building. Instead, project-specific parameters can be handled through support methods yielding distinctiveness. The ETO context hinders full parameterization.
- The distribution of commonalities and distinctiveness affects platform use and usefulness. The assets can be distributed unevenly; with Company A they focus the structural frame, while with Company B the approach so far has resulted in isolation of standards.
- Platforms and support methods in an ETO situation can focus on back-end (the supply chain) or front-end (the client) issues. Support methods within the same platform can have either back-end or front-end focus.

Also, the organization and choice of support methods are relevant to the work with developing platforms. Further studies in the field of platform performance measurement could give companies valuable guidance for support method investments.

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PAPER III

Requirements Management for the Design of Energy Efficient Buildings

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Journal of Information Technology in Construction in September 2013

www.itcon.org - Journal of Information Technology in Construction - ISSN 1874-4753

REQUIREMENTS MANAGEMENT FOR THE DESIGN OF ENERGY EFFICIENT BUILDINGS

SUBMITTED: January 2013
PUBLISHED: September 2013 at http://www.itcon.org/2013/16
EDITOR: Kirti Ruikar

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SUMMARY: *Buildings are designed to fulfil the multiple and, often, contradictory requirements of users, clients and society. Energy aspects are often not considered before the detailed design phase and a systematic way of analysing the energy performance of solutions throughout the design phase is lacking. A suggested framework, based on engineering design theories of requirements management, was applied to a case study of the design of an energy-efficient building in a real construction project. The case study provided qualitative insights into how the proposed framework can contribute to a more structured requirements management of a construction project with a focus on the energy-efficient design of buildings. It can be seen that the proposed framework for requirements management of energy performance provides a structure for designers to consider and apply energy performance criteria in the early design stages and visualize the consequences of alternative design solutions for clients, engineers, contractors and suppliers. The use of a requirements structure enables the transparency of different design alternatives against the established functional requirements of energy performance for the stakeholders in the design process. The use of BIM to support the proposed requirements framework needs to be studied further and connected to national and international construction classification schemas and ontology frameworks.*

KEYWORDS: *Requirement management, Axiomatic design theory, Energy performance, Stage-based design process*

REFERENCE: *Gustav Jansson, Jutta Schade, Thomas Olofsson, (2013). Requirements management for the design of energy efficient buildings, Journal of Information Technology in Construction (ITcon), Vol. 18, pg. 321-337, http://www.itcon.org/2013/16*

1. INTRODUCTION

Buildings are designed and constructed to fulfil the demands of users, clients and society. Many of these demands are expressed as functional requirements through building codes, standards and local regulations. The management of the many requirements throughout the design suffers from a lack of transparency which can later lead to solutions in the design process that do not meet the original requirements (Kiviniemi et al. 2005; Haymaker and Fischer 2008; Jallow et al. 2008). This results in design iterations and rework, resulting in low efficiency (Apleberger et al. 2007; Ye et al. 2009). Also, the operational islands between the many design disciplines cause ineffective coordination, figure 1, which can affect the fulfilment of the multiple and often contradictory requirements (Mattar 1983), which in turn can affect the life cycle performance of buildings (Schade et al. 2011). Proper requirements management in this context can reduce the number of design iterations and the amount of rework by providing better integration of the different teams in the design development environment (Gosling and Naim 2009).

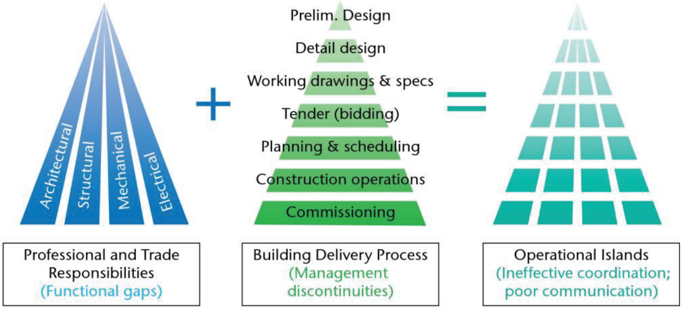


FIG 1 Operational islands from WBCSD (2008), after Mattar (1983)

Many aspects of a building's performance depend on decisions taken early in the design process (Schluter and Thesseling 2009). Space heat consumption of a building can be reduced by up to 80% if orientation, building shape, insulation and ventilation are optimized in the design process (Feist et al. 2005; Smeds and Wall 2007). Energy requirements should be considered for the entire building in the conceptual design phase and then refined throughout the design of spaces, MEP systems and components (COBIM 2012). However, energy aspects are often not considered before the detailed design phase (Schluter and Thesseling 2009), when only minor changes to the design are possible.

When designing sustainable buildings, where tendering and refinement of the product is made through a network of decisions and value processing, there are opportunities to increase design quality (Magent et al. 2009) by focusing on the integration of systems into daily engineering work. A better management of the functional requirements related to the energy consumption of the building can increase the transparency and provide better integration and opportunities for optimizing the energy performance of a building across disciplines in the design process. Schweber and Leiringer (2012) also concluded that "there is a need for research that examines the processes, understandings, and motivations which produce observed patterns and systems for energy and buildings".

The purpose of this paper is to explore a framework for requirements management in the design of buildings that enables traceability across disciplines. A conceptual framework is presented based on Suh's (2001) theories of axiomatic design and requirements-driven product modelling by Malmqvist (2001) in the field of engineering design. The framework is then adapted to a stage-based design process of energy performance as presented by COBIM (2012).

2. THEORETICAL FRAMEWORK

2.1 Theory of Axiomatic Design

The theory of axiomatic design is a systematic method for the design transformation between the customer, the functional, physical and production domains (Suh 2001). The transformations between two domains, such as the functional and physical domains, represent the design task to interpret and translate functional requirements (FRs) into design parameters (DPs), from the most generic and top-level requirement to more detailed requirement levels using zigzag decomposition cycles, see Fig. 2.

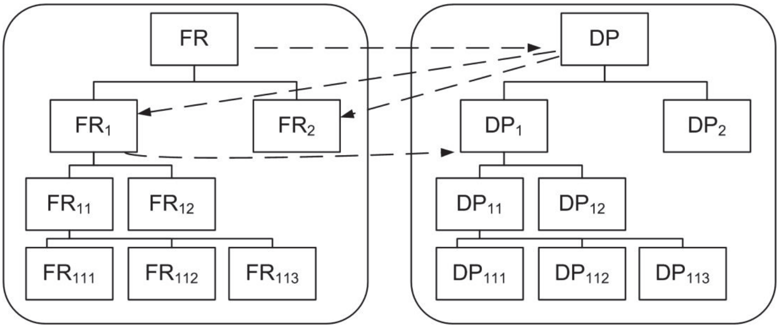


FIG 2 Zigzag decomposition in Axiomatic Design (Suh 2001)

Zigzagging is one of three basic concepts in axiomatic design where the other two axioms are:

1. The independence axiom: Maintain the independence of the functional requirements (FRs).
2. The information axiom: Minimize the information content of the design. Reduce information for the best design solution without affecting the independency of FRs.
   (Suh 2001)

The coupling between FR and DP is defined mathematically as {FR} = [A] {DP} where A is the design matrix. A diagonal (uncoupled) or a triangular (decoupled) matrix fulfils the independence axiom. However, even though this can be hard to accomplish, design solutions with as few off-diagonal elements as possible should be the aim (Suh 2001).

If two solutions have similar coupling matrices, the second axiom states that the best alternative is the solution with less information. Boundary conditions and system constraints are denoted by Cs and restrict the design space. Decisions taken from higher levels stages act as constraints at lower levels (Suh 2001).

The transformations between the domains are normally carried out by different actors with specific product views, Fig 3. In the context of construction, the *architectural view* describes the transformation from customer attributes (CAs) within the customer domain to functional requirements (FRs) within the functional domain. The *engineering view(s)* describes the transformation from functional requirements (FRs) to design parameters (DPs) in the physical domain and the *production view* describes the transformation work from design parameters (DPs) to production variables (PVs) in the process domain. Constraints (Cs) are limitations of downstream activities that have to be considered in upstream transformations, Fig. 3. These constraints can arise as a result of the standardization of components, processes or organizational conditions. Constraints can also describe regulations used at the site or conditions for transportation (Jensen et al. 2012).

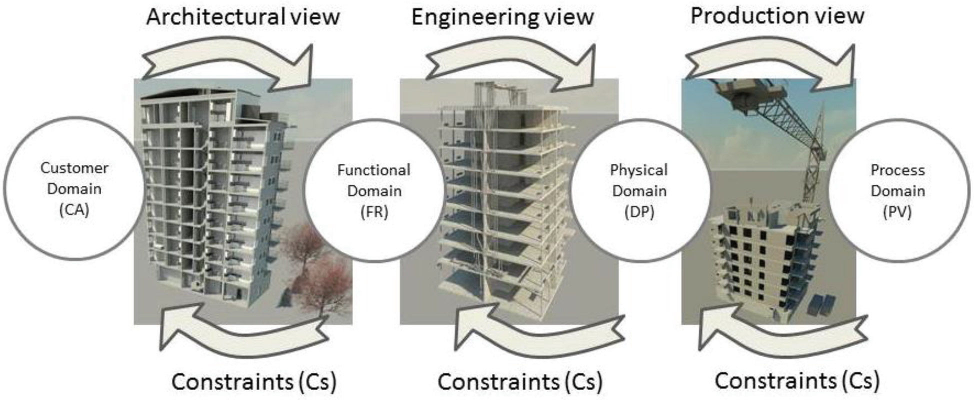


FIG 3 Axiomatic design domains and transformation of the design vectors (CA ⇨ FR ⇨ DP ⇨ PV) from different product views adapted after Suh (2001) and Jensen et al. (2012)

2.2 Requirements Management

According to Fiksel and Dunkle (1993), managing requirements is the knowledge of how to create, maintain and test requirements throughout a product life cycle. Methods of requirements management are categorized according to *eliciting, modelling, analyzing, communicating, agreeing* and *evolving* requirements for the system (Nuseibeh and Easterbrook 2000). The requirement management model by Malmqvist (2001) describes the transformation process as a synthesis of required properties for *product definition models* (described as the technical components of the product) and *life cycle system models* (described as production and supply chain systems), Fig. 4. *Property* models describe the properties of the product definition models, which are used to evaluate the performance of the design against initial requirements.

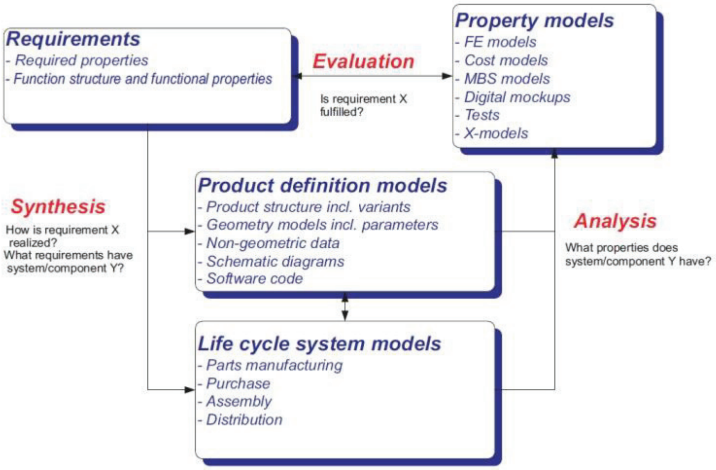


FIG 4 Requirements-driven integrated product and process model (Malmqvist 2001)

It is important to evaluate both measurable quantitative properties as well as properties that are related to qualitative stakeholder values and the functional structure of the design (Suh 2001; Malmqvist 2001).

Requirements in the construction industry are often expressed in terms of *What* is required and *Why* it is required from stakeholders such as clients and users. Design solutions express *how* these requirements should be met by the supplier side (Ye et al. 2009). However, very few research projects have focused on the gap between *what* and *why* and *how* these requirements are fulfilled by the architecture, engineering and construction industry. Kiviniemi (2005) researched how *Requirement Hierarchies* can be managed by *Building Product Models* and proposed the use of space and component objects as carriers of requirements. The transparency between requirements and solutions is another important area to consider in how to reach usability and sustainability from a life cycle perspective (INPRO-D14A 2009).

2.3 Progression in construction design

Engineering design delivers drawings, models, documents and information based on national, regional and client/customer requirements for the planning of work and supply of material to the production system. Two types of strategies can be recognized for the design work: *Point-based design* and *Set-based design*. *Point-based design* narrows down the number of product solutions in the early stages to one preferred alternative for further development. In *Set-based design,* a number of alternative design solutions are kept open to avoid iteration in the design process and to make expensive design commitments as late as possible (Choo et al. 2004). As the design progresses, the number of solutions are slowly reduced. The set-based design strategy requires more design resources and frequent meetings, especially in the early design phase. However, an early agreement on product functionality can lead to faster downstream decisions as the design progresses (Liker et al. 1996).

The use of evaluation, optimization and negotiation are examples of methods that concretize solutions in an iterative design process (Wynn et al. 2007). A concurrent engineering process can reduce lead times in the design (Prasad 1996), but the reviews necessary to ensure the quality of the design can increase the number of iterations and hence the time and cost for that design (Le et al. 2012).

2.4 Design for energy performance

Reducing the use of energy during the operation of a building is one of the most important design factors in construction projects, (Ye et al. 2009). Client requirements and local regulations regarding more energy efficient and sustainable buildings put higher demands on the design process (Malmqvist et al. 2011). So far, most energy research has been focused on methods and tools in evaluation of engineering quantitative data (Attia et al. 2012), while research on the design process for energy efficient building only represent a minor part of the field (Schweber and Leiringer 2012).

The structure of functional requirements in construction design can be decomposed from primary requirements, such as the *energy efficiency of a building*, to lower-level requirements describing measurable criteria, such as low air leakage ≤ 0.6 l/sm^2, that can be controlled using property models of the design solution (Kamara et al. 1999). It is important to include decisions that are critical for energy performance, such as the shape of the building, early in the design process (Bazjanac 2008). Therefore, several frameworks related to the design of energy performance have been proposed.

Schade et al. (2011) introduced a decision-making framework in a performance-based design process. The framework is applicable in a stage-gated design process where objective and subjective performances of design alternatives are evaluated at each gate stage. That piece of research studied an office property in Finland with the focus on the early design stages and energy performance to demonstrate the framework (Schade et al. 2011). In the common BIM Requirement defined by BuildingSMART Finland, an eight stage process for indoor climate and energy analysis is proposed from conceptual design to maintenance (COBIM 2012). Cavique and

Gonçalves-Coelho (2009) proposed a requirement structure using axiomatic design theory to reduce energy consumption in HVAC systems. The energy requirements were divided into five categories, based on the regulations in five countries in the south of Europe.

3. METHOD

The presented case study is part of a research project investigating the design management of building systems for housing. *First* a literature review regarding energy requirements, especially in the early phases of the design in construction projects was conducted. Engineering design, energy design, requirements management and design processes in construction was the base for the literature review.

Secondly a single case study was conducted to gain qualitative insights and understanding on how functional requirements are managed through design within the specific context of energy (Yin 2003). The design of a multi-dwelling house project with approximately 1500 m^2 floor area, situated in the Gothenburg region, by one of the largest contractors in Scandinavia was selected as the case study. The building system for the project is based on prefabricated concrete elements for walls, balconies, structural columns, slab floors and stairs using standard company shapes and components. The requirements of energy use in the project were essentially lower than the level prescribed by the Swedish building code. Design activities were observed in project meetings and design reviews during 2010 and 2011 with focus on the design of the energy performance. Predefined stages with gates were practiced throughout the design process. The stage-based analysis for energy performance mapped well to the proposed COBIM stages where IDA Indoor Climate and Energy (IDA ICE) software was used to analyze the energy performance of the proposed design alternatives in all three stages of the design

Thirdly, a requirements management framework was developed and proposed (detailed described in section 4).

After defining the framework, interviews with questions were formulated in four themes: process stages, requirements, energy analyses, process involvement. The first round was in-depth interviews had questions about operational work to the themes with design project managers, structural engineers and energy engineers from the house building project. Based on the result from observation made at the design reviews, semi-structured interviews were formulated with open-ended question to collect missing data and to get an overall picture of the building project. Interviews was conducted with the project manager, the design project manager, two structural engineers and the energy engineer responsible for the design of the energy performance after the building project where finished.

Finally, the proposed requirements management framework was used as a template in the analysis of the engineering work in the case study. To secure validity between interviews with project managers and engineers, the project log and related design documentation were chosen for the analysed according to all respondents. The framework was not used in the working process in the building project at the case study company but communicated afterwards to respondents and involved persons.

4. A REQUIREMENTS MANAGEMENT FRAMEWORK FOR CONSTRUCTION

The specification of design solutions according to functional requirements (FRs) is already realized in the Swedish regulation, BBR 19 (2011:26). As well as the national regulations, the client's use of the building is now part of the list of FRs. As the design process progresses from higher conceptual levels to the more detailed design of parts and components, the functional requirements also become more detailed (Suh 2001; Nuseibeh and Easterbrook 2001).

A set-based design strategy is recommended to explore multiple options, especially in the early stages when the majority of the decisions taken influence the final costs (Romm 1994). The use of virtual design methods and BIM tools are proposed to manage the design process in the search for design parameters that fulfil the requirements (Haymaker and Fischer 2008; Eastman 2008). In the case of the customization of standardized building systems, the design space is more limited. Some design parameters are already defined and act as constraints (Cs) in the design process (middle field in Fig 5), whilst other parameters can be adapted to customer requirements within fixed intervals. Parametric design of BIM objects can be used here to automatically support the engineering configuration of alternatives (Jensen et al. 2012).

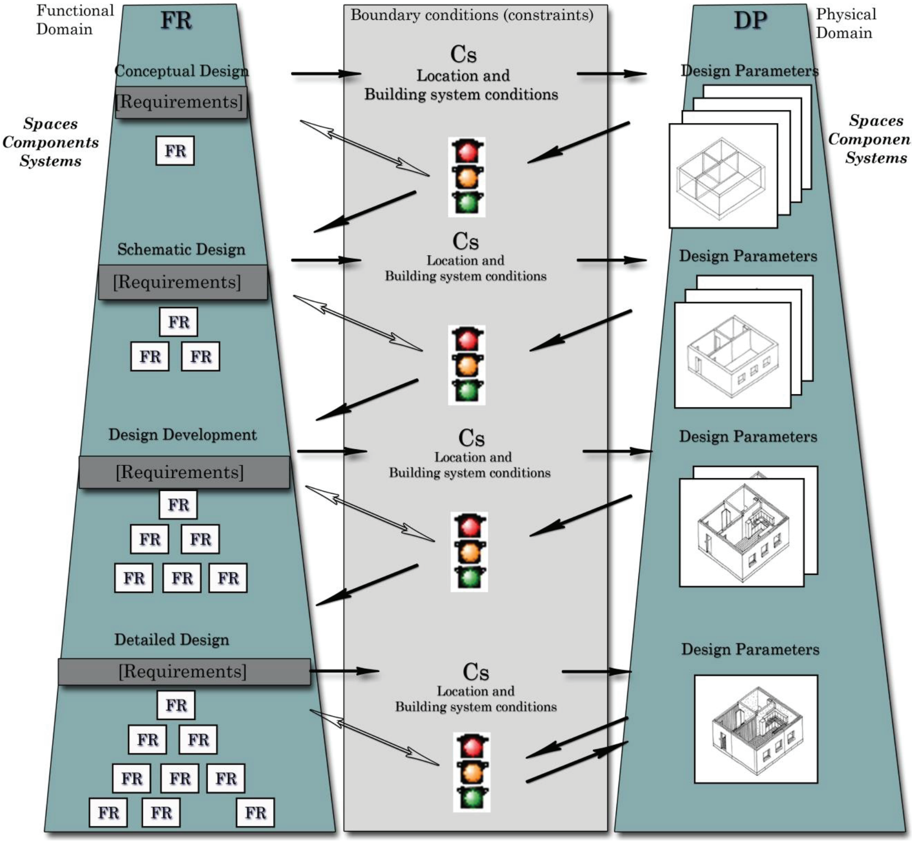


FIG 5 Proposed requirements management model

The detailing of the product is proposed to be defined in a stage-gated design process, Fig. 5, where the zigzag decomposition of FR and DP levels occurs according to the theory of axiomatic design (Suh 2001). Evaluation of design solutions from higher levels leads to new requirements at the lower levels. The use of space objects as information containers for the functional requirements can support the customer view without limiting product solutions in the early design stages (Kiviniemi et al. 2005). In later stages, components and systems can carry information regarding decomposed functional requirements at lower levels. Some BIM tools have the functionality to manage spaces, components and systems but need structures to manage the transition between functional requirements and design parameters and the relationships to building system constraints. The axioms of independency of FRs and information minimization in the proposed solutions can be used as strategies both in the design and evaluation process at each stage to secure the functionality of the product. The entire management of the design process should be based on value-adding iterations and information processing between involved actors.

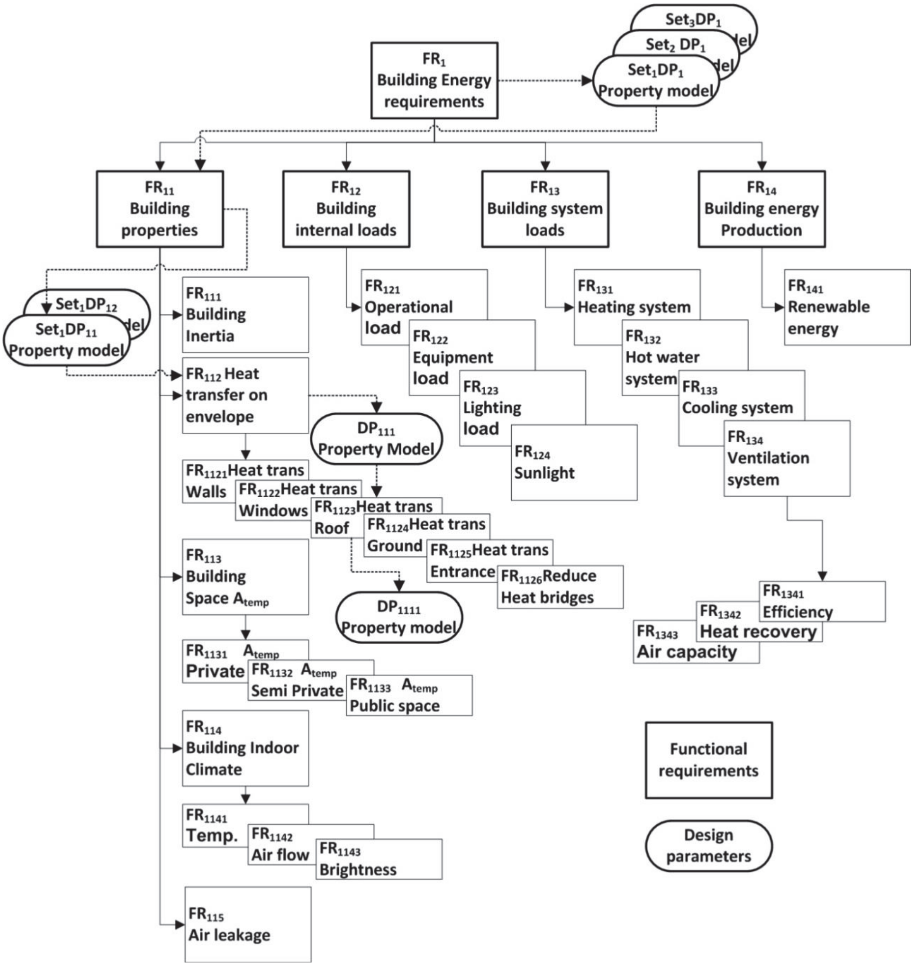


FIG 6 Energy requirements model

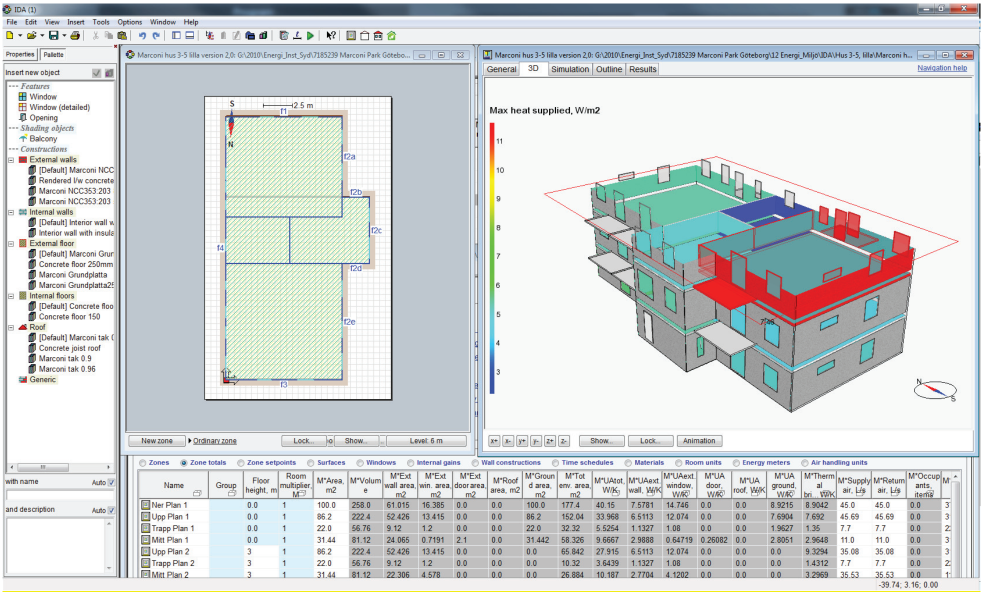
National and user requirements for the energy consumption of buildings can be mapped using different systems and components, such as the building envelope, internal gains and loads, consumption of HVAC system and the like (Cavique and Gonçalves-Coelho 2009). The common BIM requirements, developed by Senate Properties, describe a stage-gated strategy for the analysis of indoor comfort and for energy consumption (COBIM 2012). Combining Malmqvist´s (2001) anomalies (synthesis-analysis-evaluation) with the zigzag theory in axiomatic design, the energy requirements can be set up using the developed COBIM framework for energy, Fig 5. Here, the use of a Swedish classification system for building parts (BSAB 1990) will be used to enable exchange of information between design models and property models of energy (Ekholm and Fridqvist 1996). As this classification system is hierarchical, it is natural to arrange requirements in a matching hierarchy, according to the theory of axiomatic design, Fig. 6. The decomposition of energy requirements develops from both parent requirements and design parameters in the property model, Fig 6. The property model can be used to evaluate whether the performance of the design solution meets the functional requirements (Malmqvist 2001).

5. CASE STUDY

The design process at the case study company is divided into four stages: *conceptual design, schematic design, design development* and *detailed design*. A review of the design solution was conducted between each stage in the design process in respect of the requirements from the client and national codes. In the last three stages, energy simulation of 3D property models was carried out to secure the requirements for energy consumption. Even though energy simulation was part of the schematic design stage, the structural engineering work determined the progress of the design process.

5.1 Schematic design

The first energy simulation was conducted at the schematic design level, comparing different designs of the building envelope. The requirements (FRs) were determined by the Swedish code BBR15 (2008:20) and the local policy in Gothenburg, the constraints (Cs) by the location, geometrical and structural constraints and certain assumptions regarding input data not yet defined. Since only information regarding gross areas, location and building type was determined at this stage, a simplified simulation based on standard values was created for the purpose of checking basic requirements as well as to support decisions about the selection of energy supply. The simulation software IDA ICE (Fig 7) was used, in combination with a simple sensitivity analysis.



Name	Group	Floor height, m	Room multiplier, M	M*Area, m2	M*Volume	M*Ext wall area, m2	M*Ext win. area, m2	M*Ext door area, m2	M*Roof area, m2	M*Ground area, m2	M*Tot env. area, m2	M*UAtot, W/K	M*UAext. wall, W/K	M*UAext. window, W/K	M*UA door, W/K	M*UA roof, W/K	M*UA ground, W/K	M*Thermal bri... W/K	M*Supply air, L/s	M*Return air, L/s	M*Occupants, items
Ner Plan 1		0.0	1	100.0	258.0	61.015	16.385	0.0	0.0	100.0	177.4	40.15	7.5781	14.746	0.0	0.0	8.9215	8.9042	45.0	45.0	0.0
Upp Plan 1		0.0	1	86.2	222.4	52.426	13.415	0.0	0.0	86.2	152.04	33.968	6.5113	12.074	0.0	0.0	7.6904	7.692	45.69	45.69	0.0
Trapp Plan 1		0.0	1	22.0	56.76	9.12	1.2	0.0	0.0	22.0	32.32	5.5254	1.1327	1.08	0.0	0.0	1.9627	1.35	7.7	7.7	0.0
Mitt Plan 1		0.0	1	31.44	81.12	24.065	0.7191	2.1	0.0	31.442	58.326	9.6667	2.9888	0.64719	0.26082	0.0	2.8051	2.9648	11.0	11.0	0.0
Upp Plan 2		3	1	86.2	222.4	52.426	13.415	0.0	0.0	0.0	65.842	27.915	6.5113	12.074	0.0	0.0	0.0	9.3294	35.08	35.08	0.0
Trapp Plan 2		3	1	22.0	56.76	9.12	1.2	0.0	0.0	0.0	10.32	3.6439	1.1327	1.08	0.0	0.0	0.0	1.4312	7.7	7.7	0.0
Mitt Plan 2		3	1	31.44	81.12	22.306	4.578	0.0	0.0	0.0	26.884	10.187	2.7704	4.1202	0.0	0.0	0.0	3.2969	35.53	35.53	0.0

-39.74; 3.16; 0.00

FIG 7 IDA Indoor Climate and Energy with the case study building

Two different building shapes were evaluated, slab block (Fig 7) and tower block, to ensure that the consumption and installed effect did not exceed 60kWh/m^{2}a and 15 W/m^2 respectively, according to the requirements of the city of Gothenburg (Gbg). The air leakage was set to 0.6l/sm^2 at 50 Pa as defined by the regulations. The heat transfer coefficient of the building envelope was estimated to be U=0.3 W/m^2 K where the proportion of thermal bridges was set to 15%. Estimation of ventilation losses was based on a ventilation rate of 0.35 l/sm^2 using two heat recovery systems installed in the ventilation system. A duct ventilation system with no heat recovery was compared with a system that delivered a heat recovery rate of 75%. It was assumed that the building will use district heating.

TABLE 1 Examples of FRs, Cs and DPs at the Schematic design level

FR	Cs	DP
$FR_1 = Q_{energy} \leq 60$ kWh/m^{2}a (Gbg)	Cs= Climate data Gothenburg	$Set_1DP_1 =$ Slab block $A_{temp} = 1550$ m^2 => Q_{energy} 58.2 kWh/m^{2}a
$FR_{112} = U_{total} \leq 0.5$W/m^{2}K (2008 BBR 15)	Cs= Open space structural limits	$Set_2DP_1 =$ Tower block $A_{temp} = 1400$ m^2 => Q_{energy} 62.4 kWh/m^{2}a
FR_{114} = Indoor climate (Gbg)	Cs = Levels 2860 mm	
FR_{1142} = Ventilation rate ≥ 0.35l/sm^2		DP_{112} = Building envelope $U_{total} = 0.3$W/m^{2}K
FR_{1143}= Bright energy-efficient flats		DP_{1122} = Wall Brick 200 insulation U=0.16 W/m^{2}K
FR_{115} = Air leakage ≤ 0.6l/sm^2 at 50 Pa		Set_1DP_{1142} = Duct systems without heat recovery
FR_{131} =Heating performance $\leq$ 15W/m^2(Gbg)		Set_2DP_{1142} = Duct systems with heat recovery
		DP_{1143}= Attic flats
FR_{213} = 10% $\leq$ windows to net gross area (2008 BBR 15)		DP_{213} = 18% windows to the net gross area (A_{temp})

The tower block shaped building (280 m^2/floor plan) was less energy-efficient (62 kWh/m^{2}a) than the slab block building (310 m^2/floor plan, 58 kWh/m^{2}a). This difference between building shape was restricted to the number of buildings and five floor plans from the city plan. However, the recommendation from the energy analysis team was that both building types could be adapted to meet the energy requirement. The solutions were primarily evaluated from a city plan perspective and not from energy performance at this stage. The team also recommended windows with a lower heat transfer coefficient and that the air leakage be reduced. Changing to a ventilation system with no heat recovery increases the energy demand by 37kWh/m^{2}a. At the end of this design stage, a decision to continue only with the slab block building was taken from the layout of site area without analysing the glazing area parameter**.**

5.2 Design development

In the design development stage, standardized spaces (i.e. shafts and toilets) and wall thickness were added to the list of Cs as constraints of the building system along with the storey size. In the second energy simulation, the building shape, the structure and the orientation to the sun were defined. These DPs are represented by space elements in the property model. The heat transmission coefficients (U-value) for the different components in the building envelope e.g. window, walls, roof and floor slab, were set according to the recommendations in the BBR. The sensitivity analysis showed that a change of the heat transfer coefficient for windows from 0.9W/m^{2}K up to 1.1W/m^{2}K would increase the energy demand by 2.5 kWh/m^{2}a. Also, the size and placement of windows, which affects the heat gains through the incoming solar radiation, were considered in the simulation. The glazing U-values, solar properties and external shading effect on energy consumption were analysed. The location of windows and walls facing different orientations were defined.

TABLE 2 Examples of FRs, Cs and DPs at the Design development level

FR	Cs	DP
$FR_1 = Q_{energy} \leq 60$ kWh/m^{2}a (Gbg)	Cs= Climate data Gothenburg	Set_1DP_1= Slab block $A_{temp} = 1284m^2$=>Q_{energy} 57.9 kWh/m^{2}a
$FR_{112} = U_{total} \leq 0.5$ W/m^{2}K (2008 BBR 15)	Cs= Shading of the building	
$FR_{1121} = U_{walls} \leq 0.18$ W/m^{2}K	Cs= Levels 2860 mm	Set_2DP_1= Slab block $A_{temp} = 1284m^2$=>Q_{energy} 60.4 kWh/m^{2}a
$FR_{1122} = U_{windows} \leq 1.3$ W/m^{2}K (2008 BBR 15)	Cs= Structural wall 200 mm conc.	DP_{112}= Building envelope $U_{total} = 0.27$ W/m^{2}K
$FR_{1123} = U_{roof} \leq 0.13$ W/m^{2}K	Cs= Open space structural limits	DP_{1121}= 50+195+70 mineral wool $U_{walls} = 0.124$ W/m^{2}K
$FR_{1124} = U_{ground} \leq 0.15$ W/m^{2}K		Set_1DP_{1122}= Frame windows $U_{window} = 0.9$ W/m^{2}K
FR_{114} = Indoor climate (Gbg)		Set_2DP_{1122}= Frame windows $U_{window} = 1.1$ W/m^{2}K
FR_{1142}=Ventilation rate ≥ 0.35l/sm^2		DP_{1123}= Roof $U_{roof} = 0.94$ W/m^{2}K
FR_{1143}= Bright energy-efficient flats		DP_{1142}=Duct system 0.5 l/sm^2
$FR1_{115}$ =Air leakage ≤ 0.6l/sm^2 at 50 Pa		DP_{1143}=Two attic flats with dormers
FR_{131}= Heating performance 15W/m^2 (Gbg)		DP_{1241}= 6.1 % south facing windows
$FR_{213} = 10\% \leq$ windows to net gross area		DP_{1242}=79.2 m^2 south facing windows
(2008 BBR 15)		DP_{213} = 12.5 % windows to the net gross area (A_{temp})
		DP_{2131}=160.4 m^{2}of windows

In the building design stage, a more detailed energy simulation was conducted. Factors such as ventilation losses through window openings or air exhausts were included.

5.3 Detailed design

In the detailed design phase, the analyses of energy performance and indoor climate simulation were carried out to verify that the final design (DP) fulfilled the requirements (FRs), see table 3. During the design process, the national regulations were updated to BBR19 (2011:26), changing the requirements of the U-values. At this stage of the design of the heating loads, the energy use of cooling loads and heat generation was defined. Furthermore, building parts were defined to component level and validated in the energy simulation. The roof solution became one critical factor for the resulting energy demand with a late structural design of a glulam roof combined with dormers for attic apartments that resulted in a high U-value (0.94 W/m^{2}K). The specific space layout was defined and simulations of indoor climate for different ventilation systems were conducted.

TABLE 3 Examples of FRs, Cs and DPs at the Detail design level

FR	**Cs**	**DP**
$FR_1 = Q_{energy} \le 60$kWh/m^{2}a (Gbg)	Cs= Climate data Gothenburg	DP_1 = Slab block A_{temp} = 1284m^2=> Q_{energy} 57.9 kWh/m^{2}a
$FR_{112} = U_{total} \le 0.4$ W/m^{2}K (2011 BBR 19)	Cs= Shading of the building	DP_{112} = Building envelope U_{total} = 0.27 W/m^{2}K
$FR_{1121} = U_{walls} \le 0.18$ W/m^{2}K	Cs = Levels 2860 mm	DP_{1121}= 50+195+70 mineral wool U_{walls} =0.124 W/m^{2}K
$FR_{1122} = U_{windows} \le 1.2$ W/m^{2}K (2011 BBR 19)	Cs= Structural wall 200 mm conc.	
$FR_{1123} = U_{roof} \le 0.13$ W/m^{2}K		DP_{1122}= Frame windows U_{window} =0.9 W/m^{2}K
$FR_{1124} = U_{ground} \le 0.15$ W/m^{2}K	Cs= Max air Velocity/losses in ventilation duct	DP_{1123}= Roof U_{roof} =0.94 W/m^{2}K
$FR_{1125} = U_{entrance} \le 1.2$ W/m^{2}K (2011 BBR 19)		DP_{11231} = Ceiling high 2.4m
FR_{1141} = Indoor climate (21ºC) (Gbg)	Cs= Storey dimension limits	DP_{11232} = Roof structure U_{roof} =0.94 W/m^{2}K
FR_{1142} = Ventilation rate ≥ 0.35l/sm^2	Cs= Open space structural limits	DP_{11233}= Roof insulation 450 mm mineral wool
FR_{1143} = Bright energy-efficient flats		DP_{11234}= Roof structure with glulam beams 90x495mm
FR_{115} = Air leakage ≤ 0.6l/sm^2 at 50 Pa		DP_{1142} = Duct system 0.5 l/sm^2 (Mechanical exhaust air ventilation system with heat recovery)
FR_{131} = Heating performance ≤15W/m^2(Gbg)		
FR_{213} = 10% ≤ windows to net gross area (2011 BBR 19)		DP_{1143} = One three-room 101 m^2 and one two-room 71 m^2 attic flat
FR_{ij} = Requirements		DP_{115} = Taped plastic film between floors and curtain walls
		DP_{1241}=1.2 % south facing windows of A_{temp}
		DP_{1242} = 15.2 m^2 south facing windows
		DP_{131} = Heating system 14.1 W/m^2
		DP_{213} =12.5 % windows to the net gross area (A_{temp})
		DP_{2131} =160.4 m^{2}of windows
		DP_{ij} = Properties to spaces, components and systems

The size of ventilation systems was compared to the energy use of different ventilation and cooling systems, such as variable air volume and chilled beams. Here, air quality levels could also be improved or degraded with a resultant effect related to parameter changes in energy consumption, equipment sizing and thermal comfort. Also, the indoor climate at room level could be simulated for design values (DPs) by the input of requirements (FRs) when the detailing of structural and installation system had been defined. According to the energy engineer, the energy simulations were used to secure minimum requirements and were not used for optimization of energy performance until the *detailed design*.

6. ANALYSIS

6.1 Structure and transparency

The energy performance did not govern the design process, even if the energy requirement was prioritized by the client. The evaluation of energy performance was carried out on demand by the structural engineering team. The use of a stage-gate process increased the fulfilment of the requirements but the effects on the workflow were believed to be marginal according to interviews. The structure of axiomatic design with FRs, Cs and DPs was useful when visualizing inputs for decisions and analyses both in the early and later stages of the design process.

The identification, communication and decomposition of FRs, DPs and Cs broadly followed the proposed framework for quantitative requirements such as the heat transfer for the building envelope ($FR_{112} > FR_{1121}$, FR_{1122}). This visibility helped in updating the energy requirements from BBR 15 to BBR 19 when the codes changed during the detailed design phase. However, this structure was only visible to the energy design team and for the setting up of the property model and conducting of the analysis. Qualitative requirements such as *bright and energy-efficient apartments* (FR_{1143}) and *indoor climate* (F_{114}), were not decomposed and traced in the same manner as the quantitative requirements. Hence, "non-measurable" qualitative requirements lack a structure to refine their management throughout the design process (Attia et al. 2012).

6.2 Set-based or point-based iteration

The structural engineering team locked the design solution early in order to select efficient production methods. Hence, the set-based alternatives tested in the case study were limited to two building shapes (DP_1), two types of duct system (DP_{1142}) and windows with different U-values (DP_{1122}). According to the interviews, the management of multiple solutions was time-consuming.

Energy designers only participated in the three design phases where the results were used for the determination of structural dimensions and the design and selection of components and technical systems such as windows and the capacity of the ventilation system. Unplanned point-based iteration occurred in the phases *design development* and *detail design* when DP did not fulfil the energy FR. These extra iterations caused additional costs and delays (Le et al. 2012).

6.3 Space objects and functional requirements

When used as containers of functional requirements in BIM tools, space objects can be used to track FRs and Cs to manage design alternatives in the design process (Kiviniemi et al. 2005). It is also recommended by COBIM (2012) that design teams should use "*rough spatial models for alternative designs*". In the case study, only the energy requirements were mapped and made visible. According to interviews, the economic and resource risks increase if energy requirements and models were to be developed in the early design phase because of the uncertainty as to whether the project would ever be completed. However, the respondents also described early energy analysis for the evaluation of spatial requirements as being useful because of the opportunity it presents to assess the impact of the energy performance of the design solution and also the potential it has to reduce rework and non-value-adding iterations later in the design process. This equivocal attitude may be the reason for the relatively small involvement of the energy engineering team in specifying the functional requirements regarding energy and indoor climate, especially in the early design stages. The design team was more focused on the analysis of design solutions than the creation of a structure of functional requirements adapted to stakeholder values.

7. DISCUSSION

Kiviniemi (2005) wrote that the management of requirements in design is concerned with the verification of design solutions to a set of evolving requirements throughout the design process. High-level requirements that will be linked to the design need to be evaluated early in the design process. In the case studied, a gate ensuring that the functional requirements for energy were met at the schematic design stage was not set up. Also, the engineering activities for energy design were fragmented and mostly concerned with the analysis of the fulfilment of required properties of building parts and systems as proposed by the architectural and structural designers, rather than on activities based on a holistic view of a development of an energy efficient design. Operational islands, like the energy simulations performed in the case study, need to be connected to the other design disciplines by a framework with routines to enhance the transparency for the stakeholders and avoid sub-optimization along with unnecessary design iterations. Axiomatic design offers a structure to manage requirements and constraints in relation to design parameters (solutions) by systemizing them in a supporting structure. In the case study, areas other than energy such as fire, acoustics and environmental considerations also generated new requirements as the refinement of building design progressed.

Alternative design solutions were tested to some extent in the case study. However, the alternative design sets were few and rapidly abandoned in favour of one solution that progressed as a point-based design strategy. The opportunities to manage multiple solutions by using methods such as parametric 3D modelling and rough spatial models need to be developed in practice. The requirement structures derived from the theory of axiomatic design are of benefit for all stakeholders in building projects such as clients, project managers, suppliers and end-users (Ye et al. 2009). However, these structures need to be transformed between different views, connecting customer values with engineering design and production specifications (Malmgren et al. 2010; Jensen et al. 2012). Therefore, the use of spaces objects is recommended to communicate and transform client values into requirements.

Managing all the technical expertise required at the early design phase increases information complexity and can be time-consuming. Here, an integrated concurrent engineering approach, where functional requirements are centrally stored, decreases the non-value-adding iterations in the design process (Jallow et al. 2010) with a lower cost and higher quality as a result (Chachere 2009). The study of how energy requirements can be managed using the principals of the axiomatic design theory only shows a small part of how the theory can be applied to the design of buildings. In the axiomatic design structure, a client's involvement and values need to be considered because, according to Kamara (1999), both qualitative and quantitative functional requirements are related to the voice of the customer.

8. CONCLUSIONS

This paper presents a framework based on the theory of axiomatic design to support the management of requirements in building design. By studying this framework within the context of managing energy requirements in the design of buildings, the following conclusions can be made:

- By identifying and making more transparent the functional requirements (client's, local and national regulations) and downstream constraints (from engineering, production and supply) in the design process, better support for selecting strategies and decision-making is created.
- A set-based design strategy together with the theory of axiomatic design can be used to manage and evaluate the performance of multiple design alternatives (DPs) against the established functional requirements (FRs).
- The proposed systematic requirement framework for energy performance can empower designers to consider and apply energy performance criteria right from the early schematic design stage.

The use of BIM to support the proposed requirement framework needs to be studied further and connected to construction classification and ontology. Also, further research is needed on how model-checking tools can be used to compare requirements (FRs) with the performance of design solutions and defined constraints (Cs). The use of FRs, Cs and DP structures can probably be reused as components with associated design and production activities. Finally, more research is needed on how to include other functional requirements in the proposed framework such as acoustic, environmental, moisture and fire requirements and how these can be managed concurrently throughout the design process.

8.1 Acknowledgements

This work was carried out within the competence centre of Lean Wood Engineering. We gratefully thank the respondents at the case study company for their time and inspiration. This work was funded by the Swedish Governmental Agency for Innovation (VINNOVA), the Centre for Energy and Resource Efficiency in the Built Environment (CERBOF) and the Development Fund of the Swedish Construction Industry (SBUF).

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PAPER IV

Continuous development of house-building platform through experience feedback

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Submitted for the Journal of Construction Innovation in October 2013

Continuous development of house-building platforms through experience feedback

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Abstract

Purpose – House-building companies seek improvements to decrease costs, improve flow, and decrease variability. Industrialised concepts using predefinitions in platforms have become one strategy to store and reuse knowledge in house-building organisations. The aim is to describe how building projects and product development contribute to platform development through experience feedback. All solutions are not predefined in a house-building project and design work is performed in each project. The platform supports the building projects through different support methods applied in the design phase.

Design/methodology/approach – Four different channels for experience feedback were studied at one house-building company in Sweden. To identify and discuss the underlying structure for managing experience feedback for platform development a case study approach was chosen combined with a qualitative collection of data through interviews, archival studies and observations. The data is explained using an analytical framework based on a literature review on platforms, experience feedback, continuous improvements and house-building building supply chains. Furthermore, the interaction between building projects, the platform, the support methods and experience feedback is illustrated.

Findings – The paper identifies how experience feedback is fed through several channels to improve the platform over time. By using multiple channels with differing content, it is possible to balance client demands and variation with production efficiency. Platform development creates a holistic view of a wholesale product fulfilment for both the demand and the supply side. Operative work in projects together with strategic decisions made by developers continuously develops the platform.

Originality/value – The production chain becomes central for how to manage and control experience feedback in the organisation. A time perspective of platform development in house-building challenges both the prevalent project view but also the emerging product view in house-building. Integrating the design phase in the supply chain enables variety but also creates demands on constant development in order to keep the platform updated.

Keywords – Platform, Development, Supply chain, Experience feedback, Continuous improvements, Sweden

Paper type – Case study

Introduction

House-building companies seek methods to improve the flow through their design and production processes. By higher predefinition of components, systems and related processes in house-building projects, time and costs can be reduced (Winch 2003, Voordijk et al. 2006, Vrijhoef et al. 2009). The product platform (Robertson and Ulrich 1998) perspective, based on predefined components and modules arranged in a product architecture, is developed in house-building using continuous improvement from day-to-day work experience (Thuesen and Hvam 2011). Halman (2003) presented the expected benefits of using product platforms as; flexibility in product design, efficiency in product development and realization, and effectiveness in communication of market position. The complexity in applying a platform in industrialised house-building is not to define the physical building system, but to balance the company predefinitions that give economies of scale with the development of relations in the supply-chain, which produce variety in product design (Voordijk et al. 2006, Hofman et al. 2009). Meiling (2010) showed how different experience feedback methods interact to promote sustainable continuous improvements for house-building production chains.

The main challenges in project organisations are that decentralisation, short-term emphasis on project performance and distributed work practices create their own logic of action. This inhibits knowledge transfer to use the power of differentiation (Bresnen et al. 2004). House-building companies are focused on profits of developing land rather than improveing their own house-building process (Winch 2003, Pan et al. 2012). Despite substantial investments in platform development in Sweden little research attention has been paid to the development of platforms for house-building and how to use it over time (Ingemansson 2012, Jonsson and Rudberg 2013). There is a limited understanding of how to capture and transfer onsite production experience to gain knowledge in coming design and on-site production processes (Gerth et al. 2013, Lam and Wong 2009). During the latest decade platforms for house-building have become a system for storing knowledge and predefinitions for house-building components, related processes, and internal and external relationships, figure 1 (Jansson et al. 2013a).

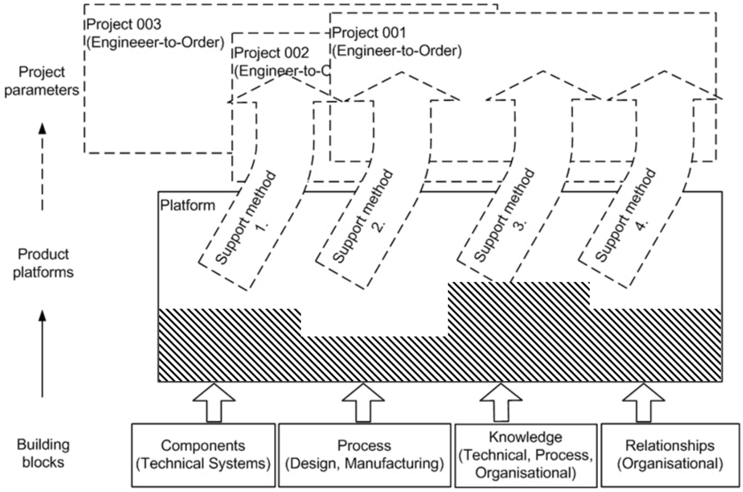

Figure 1. The function of a platform in an engineer-to-order supply chain (Jansson et al. 2013a)*.*

The process of transforming customer demands and requirements to design solutions that fit house-building production and supply chain variables can be systematised to support day-to-day design work (Jansson et al. 2013b). Platform use in house-building is the transformation of project requirements to building solutions supported by predefined solutions and constraints in a platform, figure 1. Components, processes, knowledge and relationships have been identified as assets for supporting the design work in industrialised house-building (Jansson et al. 2013a). Design work becomes crucial because the client enters the process in the design-phase in engineer-to-order (ETO) supply chains (Gosling and Naim 2009). To update the platform and to improve assets to better support the work a knowledge flow from projects to the platform is missing.

Systems to manage knowledge in the design-phase are needed for managing relationships between actors in the supply chain (Thuesen and Hvam 2011, Jansson et al. 2013a, Haug et al. 2009). Standardised processes based on proven technical solutions are a basis for collecting and storing experience data in house-building systems (Meiling 2010). Introducing platforms are a risk for organisational inertia and might lead to difficulties to balance different stakeholder demands (Karlsson and Sköld 2007). On the other hand, the introduction of platforms in house-building causes the company to move from ETO towards make-to-order (MTO) production, which is described as a movement towards mass customization (Winch 2003). To keep this movement within the boundaries set by the company strategy, constant evaluation of the balance between commonality and distinctiveness in the platform is needed. Thus, making use of experience feedback from projects is interesting for finding this balance (Robertson and Ulrich 1998). The balance will change over time when experiences continuously are fed back to update the platform.

The aim of the study is to describe how a combination of project work and product development can balance platform development over time in the context of house-building. Prior research in industrialised house-building has not paid attention to the continuous development of platforms in an engineer-to-order (ETO) context. Furthermore a systematised perspective is missing of how experience feedback flows (Styhre and Gluch 2010) to and from the platform.

Platforms in the make-to-order context

A product platform is the stored knowledge about components, process and relationships (Robertson and Ulrich 1998, Meyer and Lehnerd 1997). Platform planning process involves a *product plan* for options, a *differentiation plan* to make sure that the models differ to attract customers in different market segments, and a *commonality plan* that describes where products in the plan share the same physical elements (Robertson and Ulrich 1998). When developing the *product plan* for platforms three development steps are taken: market positioning, product realisation, and manufacturing processes (Robertson and Ulrich 1998, Meyer and Lehnerd 1997, Simpson et al. 2006). In order to provide customization and maximize the economy of operations, Bowman (2006) suggests that the marketing positioning in the product plan is defined by starting from the front-end with customer needs. To understand market needs, platform developers have to incorporate knowledge of their own product, competitors, material and technologies, but also internal capabilities in cost savings, flexibility and functionality. They are therefore dependent on strong collaboration with market personnel for platform development (Meyer and Lehnerd 1997). The next step, according to Meyer and Lehnerds' (1997) platform planning, is to ensure that product functions and applications accommodate the flexibility in the market segment. The last step is to integrate manufacturing processes with the platform taking in aspects of using subcontractors and matching labour cost for assembling.

Finding the proper balance between commonality (for minimising costs and create flow) and distinctiveness (for uniqueness and differentiation) in products is one of the major challenges in platform development. To overcome it, suggestions are to construct a modular design, or to consolidate to delay product differentiation of parts or elements in the production chain (Robertson and Ulrich 1998).

The *differentiation plan* is more detailed than the *product* plan and focuses on comparing target values between different products using metrics for different requirements starting at the overall properties and then going into details. Detailed platform planning in a *differentiation plan* is made by measuring the importance of unique values by differentiating attributes (DA´s) for the product, to each stakeholder (i.e. client, purchasing, production manager) (Robertson and Ulrich 1998).

The *commonality plan* is cost driven in developing and producing reusable physical elements and minimising unique parts. Commonality, modularity and reusability of elements in the commonality plan are estimated. From several studies of the automotive industry, Robertson and Ulrich (1998) proposed a process for platform planning:

1. Help the organisation to understand that there is a trade-off between commonality and variety.
2. Drive for quick approximate results and challenge the company to evaluate platform architectures to commonality and distinctiveness.
3. Push for facts on customer needs, size of segments and cost of differentiation.
4. Avoid insisting on total agreement but ask for design solutions that everyone agrees are good enough.
5. Start at the top level of the product and then iteratively refine the plan in details.
6. Make the process a living one by continuous evaluation and improvements.
7. Evolve the planning process by more members to be involved for better understanding.
8. Use results to drive the improvement agenda for the company in platform development.

Component commonality in product variants leads to similar or repeat operations, activities and sequences among process variants (Schierholt, 2001). The correlation between process and components, also leads to correlation between product variation and process variation. From the platform, design, manufacturing and assembly process variants can be derived (Jiao et al. 2006).

In a state-of-the-art review of product families and platform development, Jiao et al. (2007) provides a development framework based on Suh´s (2001) design domains that follows product realisation, figure 2. The framework focuses on how to develop products that widely variegate design to customised requirements not only from keeping variant forms of the same solution, but also in modelling the design process of an entire class of products.

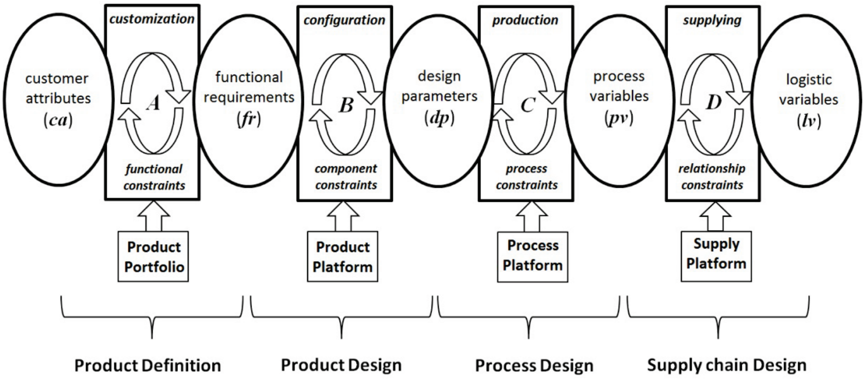

*Figure 2. Product fulfilment by platform and portfolio plannin*g (Jiao et al. 2007).

Jiao's (2007) framework, in figure 2, involves the mapping between the five domains of product definition by aligning platform design as an effective means to achieve economy of scale. Product portfolios and platforms store and support the mapping between domains in the work with product definition, figure 2. To map the benefits of platform development, a holistic view of development has to be applied from the demand side passing through all domains in the design and manufacturing chain. In the product development process, product platforms support the engineering work by reducing: development cost, time, manufacturing cost, production investments and complexity (ibid). The challenges of simplifying or trivializing engineering work can lead to unfortunate consequences; loss of innovative capability, chance of imitation, organisational resistance, and a limitation in the amount of clients by prioritising cost (Karlsson and Sköld 2007). Product family evolution by renewing platforms into generations either extends to new products or redevelops in new versions of platforms, shown in figure 3.

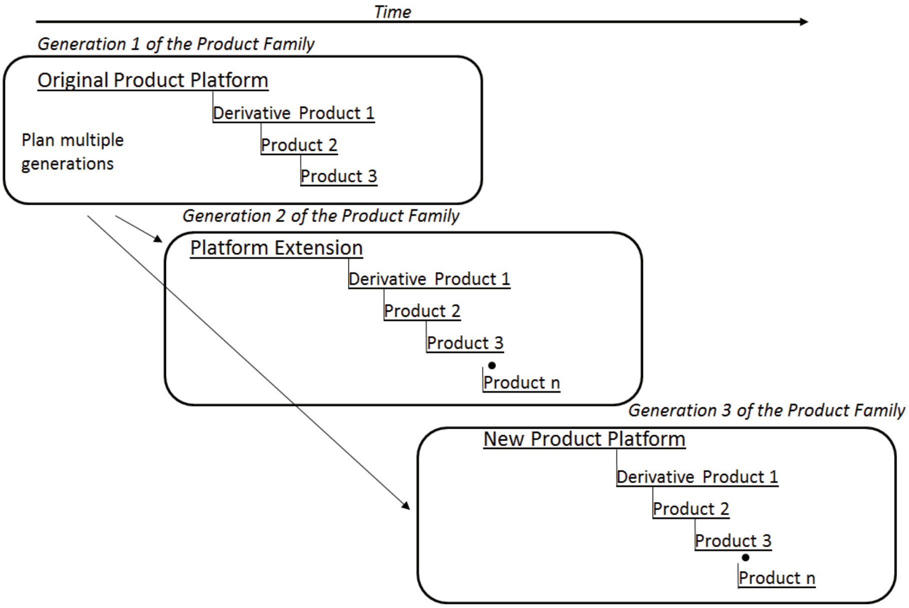

Figure 3. Product family evolution, platform renewal, and new product creation (Meyer and Lehnerd 1997).

In Meyer and Lehnerds' (1997) study of computers, the development of platforms is done separate from production and in generations of product families. Derivative products are generated from the platform through releases to be put into production and also new product platform releases to be used in product development, figure 3. In the next platform generation, some subsystems and interfaces remain constant, but some are redesigned in order to achieve cost reductions or to allow new features.

The concept of developing platforms by a combination of knowledge flow from production experts together with experience from product development is a foundation for platform development (Karlsson and Sköld 2007, Alizon et al. 2007, Wortmann and Alblas 2009).

Continuous improvement of standardised systems

Imai (1986) describes development for fast-growing organisations by *innovations* in large steps of improvements that require sophisticated techniques, research and technology. The *kaizen* approach of improvements, that suit slow-growing organisations, uses many small improvements where the use of tools and methods are trivial to use for design and production (i.e. pareto charts, root cause analysis and tree diagrams). The foundation of *kaizen* assumes that everybody is involved in the improvement work. Imai (1997) proposed that continuous improvement of a long-standing process is achieved by introducing innovations in improvement steps and then apply kaizen to stabilize the process at the new level, figure 4.

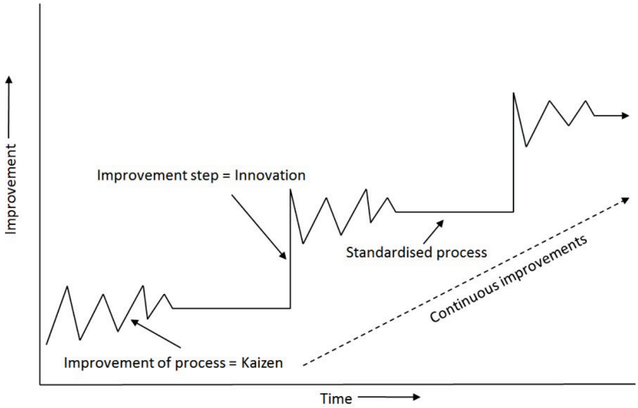

Figure 4. Improvement steps and standardisation (Imai 1997).

Standardisation of operations means to find the stability in the process and perform the work better next time (Imai 1997). Feedback is the interaction between a system and its surroundings. When experience from practical use of a system is fed back, it becomes an input that shapes future improvements of the system correcting actions from actual to desired performance (Åström and Murray 2010).

Platforms in the engineer-to-order context

House-building design is a transformation process of project requirements to building solutions and is set in an ETO supply chain (Gosling and Naim 2009). For house-building, the main purpose of the platform is to share, visualise and control projects in a decentralised organisation where collective experience disappear or is brought forward to the next project (Styhre and Gluch 2010). Because house-building projects seldom repeat themselves completely, the MTO concept of product families is not applicable in the ETO context (Jansson et al. 2013a) and configurations in each building project represent the engineering transformation to solutions. In the day-to-day engineering work, variation is related to the level of standardisation in the platform (Jensen et al. 2012). The development of house-building platforms therefore takes incremental steps towards a platform with knowledge that flows in the organisation and knowledge stocks that are stored as predefinitions (Styhre and Gluch 2010). Gerth et al. (2013) claim that when using a house-building platform, project experience should not be analysed and improved in separate product development. Instead, product configuration in the design-phase should affect the entire supply chain, for each building project, which leads to improvements for the entire system (ibid.).

The house-building supply-chain is associated with project organisation that uses multiple support methods, but seldom has an overall operational strategy (Winch 2003). The use of platforms in house-building design process is supported by different methods and the platform development is integrated in day-to-day work (arrows in figure 1), (Jansson et al. 2013a). Factors for using platforms successfully in house-building are how the organisation uses flow-based processes to meet variety and how customisation is met by distinctiveness in the platform (Veenstra et al. 2006). Styhre and Gluch (2010) describe the platform for construction as boundary objects helping to integrate forms of know-how and experience for design work and a mechanism that is potentially capable of balancing accuracy and flexibility.

The customer order decoupling point (CODP) is located at the design stage in the ETO context where each product is different to the last (Gosling and Naim 2009). A platform approach with standardisation in the ETO context puts demands on how to validate the investment in standardisation (Haug et al. 2009). To avoid standardisation that limits value-creation for the client Jonsson and Rudberg (2013) claimed that the ETO context has to be characterised by: product type, production system, degree of product standardisation, production volumes, degree of off-site production and order-winning manufacturing output.

Industrialised house-building shows a range from near make-to-order (MTO) production (with some undefined parameters for client choices), over to project-based construction close to a concept-to-order (CTO) production (with a large number of undefined variables). House-building projects with wholesales commitment have shown how projects are met by platform predefinitions using support methods, however, with apparently little focus on experience feedback from projects (Henderson et al. 2013).

Experience feedback in construction

In many house-building projects, problems are solved through fire-fighting where projects in isolation do not detect, uncover and address root causes of underperformance (Henderson et al. 2013). Methods available to manage experience feedback are not usually developed for construction and even small incremental improvements need to be related to client satisfaction in the project to be motivated (Meiling 2010). Much of the knowledge in construction is personal or community-based (Styhre and Gluch 2010) and connections between relevant experience from project meetings becomes feedback first when they are targeted to someone in the supply chain (Meiling 2010). Experience feedback in construction has to be communicated through experience sharing driven by a pull from actors or systematised for continuous improvement when the experience is needed in projects in order to minimise data loading and information overload. The ability to manage construction projects demands good management of knowledge in the organisation, because much of the collective experience disappears when a construction projects is finished (Styhre and Gluch 2010). The project-based industries in construction with decentralised organisations form local practices which seldom make use of the knowledge flow in the organisation and the repetition of work between units (Styhre and Gluch 2010). In order to manage knowledge transfer to projects, central systems that link organisational knowledge with task completion for project differentiation enables both short-term performance in operational work projects but also long-term benefits in the strategic development of construction firms (Bresnen et al. 2004).

Method

An inductive case study was performed studying four channels of experience feedback for platform development. By choosing a case study research approach and analysing systematised feedback in the ETO context, platform development can be widened to apply to the studied context (Yin 2003). Using engineering design methods and analysing them to the platform development by experience feedback in an ETO context a framework can be developed. The experience feedback flow in a house-building platform was the unit of analysis where the study was designed to describe how improvements can support continuous platform development over time.

Design of the case study

The case study gives an opportunity to study channels to manage the knowledge flow of experience from operational work and how the knowledge has been systematised. By choosing one house-building company with a decentralised organisation, challenges in platform development covers most of the supply chain. One large Scandinavian house-builder was selected for the case study due to their: platform investment in predefinitions, the multiple channels of knowledge feedback from house-building projects and their work with continuous improvements of platforms. A fragmented and decentralised organisation limits collaboration and limits knowledge transfer in a production system (Karlsson 1992), which motivates the choice of the house-building context where companies today have to manage development within building projects. The experience feedback flow was categorised using Robertson and Ulrich’s (1998) advice on platform development. The case company uses on-site production in an engineer-to-order context where the clients are met in the design phase. Company standardisation of building components and work procedures is performed by platform managers. The use of different experience feedback channels was interesting for the study because it gave multiple data sources for the analyses of platform development.

Data collection and analysis

The data collection methods were interviews combined with observations and platform documentation from ten building projects. The four experience feedback channels were observed and documented by taking notes. Interviews gave the opportunity to see the world from the respondent's view (Kvale 1995). Four platform developers, as experts who analyse consolidated experience on the strategic level (two building, one process, and one system developers), in the organisation were interviewed in structured interviews with open-ended questions aiming to grasp their focus areas and the purpose of the channel of experience feedback channels. Archival data from the four channels (which are in use of the company) was collected from project-, platform-, log and feedback documentations. To map the house-building predefinitions to the supply chain, platform constraints and feedback methods were quantified and categorised following Jiao's (2007) platform development model with the categories: *functional requirements, components, processes* and *relationships.* Thereafter platform constraints and data in the feedback channels were sorted in commonality and distinctiveness according to Robertson and Ulrich's (1998) platform planning.

To be able to gather improvement comments from the entire organisation the company has invested in a feedback system with a channel called *Your point of view*, that logs experience feedback as individual reflections for platform improvements. The feedback system is implemented in the enterprise resource planning (ERP) system where individual knowledge, experience and improvements are canalised. The purpose with *Your point of view* is to continuously develop platform predefinitions, reachable for all employees in the entire organisation. Data was collected from feedback reported in the channel 2006-2012.

Design optimisation is implemented as a routine for improvements in every project. It is a channel that collects knowledge from projects by evaluating performance criteria as go/rework/not go further in the design process. The channel focuses how predefinitions from the platform are used and how choices that lie outside the platform predefinitions are motivated. *Design optimisation* is intended to be done twice in each project. Building project teams prepare an internal review one week before the design optimisation is executed by platform developers. Routines and documentation supports the preparation work from the platform. The purpose of the channel is to evaluate costs and choices from a production perspective compared to platform design parameters. Collected from all ten projects.

Improvement meetings are a channel that is organised at a regional level. Developers, engineers and construction managers from different projects meet about every month to analyse and improve the design work and related support methods with their different views. Topics are transferred to other groups for investigations or further improvements by platform managers, project managers or in design work. As a cross-organisational meeting, this data source was interesting for the focus on platform alignment and with a predefined aim to focus on relationships and processes in house-building projects. Participating observations and documentation of five meetings were performed in conjunction with interviews of platform managers. Collected at seven meetings under the year of 2011.

Client feedback meetings are performed by the company at the project level to capture experiences from clients and project managers that meet after project delivery to document the client experience, follow-up deliveries, quality, and communication. These meetings follow a predefined schedule with a questionnaire that every client fills in. The aim of the *client feedback meetings* is to improve the platform but also to secure customer satisfaction in deliveries. Collected from the ten studied projects under 2010-2012.

Case study results: platform predefinitions

The case study company continuously documents platform predefinitions (hatched fields in figure 4). House-building projects have a cycle time of about 2-3 years for designing, building and delivering a complete multifamily house to the client which in all cases was the internal property development division. The use of platforms at the case study company has a dominant focus in design where planning for the production process is central. Predefinitions in the platform have the purpose to support customization, configuration, production and material supply. In order to support early communication with clients and stakeholders in projects, about 80 *functional requirements* are documented in the platform (hatched field of product portfolio in figure 4). *Functional requirements*, following national code requirements, are given levels in the platform in eight categories of functions; layout shape, sustainability, fire, inner climate, usability, acoustics, safety and energy. Less than half of the *functional requirements* are linked to *components, processes,* or *relationships* in the platform.

Of the 383 *components* (product platform bar in figure 4) 225 are documented as detailed solutions (e.g. sockets, windows, doors), 110 are documented on the building element level (e.g. curtain walls, balcony solutions, stairs) and 23 are on a sub-systems level (e.g. ventilation, structural, roof system). The remaining 25 are layout solutions that describe the interior and exterior layout from service shafts up to site layout predefinitions. *Components* are formulated as single solutions in about 2/3 commonalities and 1/3 are formulated as variable for distinctiveness. The solutions are transferred to projects by support methods, but also stored as templates and solutions in CAD (Computer Aided Design) systems.

Platform production *activities* are stored and organised in sequential order without predefined timelines. Each *activity* has detailed descriptions with checklists, delivery plans, and recommendations for how design and manufacturing activities should be executed. Of all 398 documented platform *activities* (hatched process platform bar, figure 5) 251 concern design, 49 purchasing, and 98 production *activities*. The use of platform *activities* for planning of projects is individually made by project managers with the purpose of streamlining work for better flow. Early design-phase *activities* in the *process platform* focus on economy estimates, investigations, interrelations and cooperative agreements. Later design phase activities focus on deliveries of models, reports, contracts, descriptions, drawings, schedules and purchasing documents.

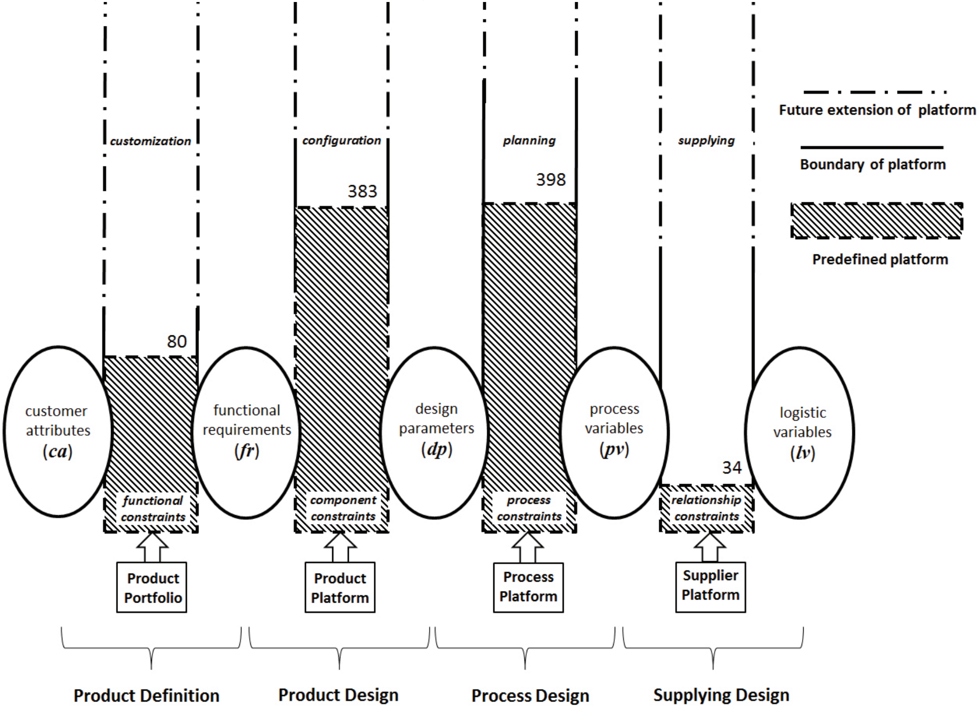

Figure 5. Platform predefinition at the case company.

Relationship predefinitions are stored in both early steering documents and purchasing documentation with rules and recommendations with the purpose to reuse knowledge of suppliers in the *supplier platform*. The areas environment, energy, moisture and fire all have relationship predefinitions defined identifying area specific engineers in the platform that were applied in the studied projects. 34 relationship predefinitions were formulated in the supplier platform dominated by company agreements but also contractual relationships for suppliers were defined.

Knowledge documents in the platform motivate and backup standardisation. Knowledge documentation works as a link between physical systems (components), working methods (processes) and organisation of resource operations (relationships). They have a function of supporting choices by describing benefits and disadvantages of using certain components and how the choice affects the client and the production process requirements. Knowledge documentation describes properties in nine terms: structural stability, fire, internal environment, safety, acoustics, energy, maintenance, aesthetics, and user-friendly dimensions.

Case study results: platform feedback channels

The development of a platform is done with central expertise that uses their experience of managing house-building projects by support from each technical and functional discipline (structural, energy, moisture, acoustics, aesthetics, usability, HVAC, ground and foundation). Platform managers use the experience feedback from the four studied channels for development and for measuring to what extent the platform is used in the organisation.

Table 1. Focus in experience feedback methods

Platform feedback channels		Variables (for distinctiveness)	Solutions (for commonality)
Your point of view	Components **74 %**	28%	46%
	Processes **18 %**	4%	14%
	Relationships **8 %**	0%	8%
Design optimisation	Components **75 %**	24%	51%
	Processes **19 %**	14%	5%
	Relationships **6 %**	2%	4%
Improvement meetings	Components in **20 %**	2%	18%
	Processes **34 %**	7%	27%
	Relationships **46 %**	17%	29%
*Client feedback meetings**	Components **21 %**	13%	8%
	Processes **26 %**	26%	0%
	Relationships **53 %**	30%	23%

*Company´s predefined questionnaire

Design optimization and *Client feedback meetings* represent project specific experiences that develop the platform. From *Your point of view* and *Improvement meetings* general improvements are specified to develop platform constraints, see table 1.

Platform component constraints have a total share of 74% in the channel *Your point of view*, table 1 where 28% of component are variables (e.g. windows < 40 dB, plinth height < 400 mm, balcony slope < 1:50) and 46% are component solutions (e.g. storey height = 2860 mm, air gaps in facades = 30 mm, kitchen faucets). Through *Your point of view,* 18% were suggestions on process improvements with 9 out of 10 concerning production process solutions (casting, sheet metal work, painting, etc.) and 1 out of 10 design process solutions (CAD-drawing, calculation, planning, etc.). Because only 4% of the process improvements channelled through *Your point of view* were formulated as variables (work interfaces, design process order, bathroom work, etc.), focus was on finding by repetition in work. 8% of all improvements in *Your point of view* represent relationships and half of these improvements are related to suppliers and the rest to contracts and inspections. None represent resources or organisational issues to improve prediction of the design work.

Design optimisation is performed twice in each project and is the largest feedback channel. The improvements concerning *component constraints* constituted 75%. The most recurrent improvement concerns layouts (e.g. WC/Bathroom, stairwells, shafts, etc.). Through the channel *Design optimisation,* 51% of the improvements were formulated as component solutions and 25% as variables. The feedback in *Design optimisation* focus on detailed components and their use, how work is planned and executed, but also how teams can be organised for better design deliveries.

Improvement meetings are a channel that handles organisational issues and organisational relationships, which constitutes 46% of the feedback comments. Meetings are held with questions on how actors should be involved and their responsibilities to interact in the design process. Property developers (the internal client), technical experts, contractors, and platform developers meet to improve the house-building product by focusing on design and production routines, and responsibilities and contractually regulated interconnections. Meetings have a clear purpose to open up questions for platform use and development, where questions are formulated for the supply chain instead of for individual projects.

Client feedback meetings are held together with the client, sub-contractors and suppliers. A questionnaire is predefined by the case company and formulated to collect experience from clients with a dominant focus on relationships (53%) both to themself and also to subcontractors and suppliers. The result from the ten studied projects showed a dominant focus on variables for relationships from clients (30%). 26% of processes were formulated as variables and none as solution. The entire questionnaire was formulated by variables with of results by answers of 69% comparing to 31 for solutions.

Table 2. Platform and experience feedback channels

	Platform predefinitions	*Your point of view*	*Design optimisation*	*Improvements meetings*	*Client feedback meetings*
Platform assets	**Components/ Process**	Components (74%)	Components (75%)	Relationships (46%)	Relationships (53%)
Level of platform predefinitions	**Detailed**	Layout	Layout	System	Detailed
Experience feedback perspective		Supply chain (weekly)	Project (after engineering)	Supply chain (every month)	Project (after delivery)
Levels for improvements		Push from operational	Pull from strategic Push to operational	Pull from operational	Pull from strategic
Formulation of platform predefinitions and improvements	**Solutions (60%)**	Solutions (68%)	Solutions (60%)	Solutions (74%)	Variables (69%)

Of the nine functional requirements in the platform only energy, fire, moisture, and acoustics were represented in the feedback data from all the channels (representing 8% of total feedbacks). Of all comments from the feedback channels, components were dominating output for the design-phase, table 2. The feedback method *Design optimisation* focuses on component constraints from the platform with a pull for improvements from the platform developers. *Your point of view*, which is the feedback method that is open for all actors in the process, is less frequently used than *Design optimisation* and with a main focus to push improvement solutions for components (i.e. structural framework of the building). Functional requirements in knowledge documents were used in design to support realisation of technical components for the building project.

Platform development in an ETO context

The study showed how experience feedback was integrated in the organisation and how different channels affect the feedback for development of the platform. In house-building, design work is integrated in the production chain due to the platform being only partly defined (Jansson et al. 2013). Functional requirements were identified in the platform studied. More than half of these requirements were not connected to components, processes or relationships. For those who were connected, they were only linked on a detailed level. Improvements of functional requirements in the platform were only documented in the channel *Your point of view*. *Design optimisation* documented a platform focus on the latter part of design with a supplier perspective on components. *Improvement* and C*lient feedback meetings* channelled methods to manage organisational relationships in the platform. Together, the feedbacks channels address all the building blocks in a platform, figure 1. To find a process to develop a platform, Robertson's platform planning is evaluated in the house-building context. The eight steps of platform planning are translated and explained using data from for the studied experience channels and knowledge from other researchers, table 3.

Table 3. Platform development in MTO and ETO contexts.

Platform development in an MTO context. Robertson and Ulrich (1998).	Platform development by experience feedback in an ETO context exemplified by house-building.
Help organisation understand trade-off between commonality and variety.	Companies need to communicate internally how to balance their platform commonality and distinctiveness, but also how to handle non-defined parts in building projects. From the case study the main experience feedback concerned component commonalities. Over time, this could lead to a narrowing of the platform and the product offer, but also cause organisational inertia and become difficult to balance with stakeholder demands (Karlsson and Sköld 2007). The case study company uses an open platform, which meets client and production variations (Winch 2003).
Quick approximate results to evaluate commonality and distinctiveness.	The projects studied have a cycle time of about 2-3 years and use the feedback as a frequent knowledge flow with the dominant focus on components. Creating balance in a platform takes time and continuous market positioning is key to successful platform planning. Decreasing cycle times and increasing speed in the entire production process has been beneficial for the profit in house-building (Thuesen and Hvam 2011). The improvement meetings studied show how analyses from a supply chain perspective created pull for improvements as a valuable source for differentiation. It is also interesting to find that three out of four studied feedback channels bring suggestions of solutions instead of variability. The platform predefinition is documented as solutions in two thirds of the cases.
Facts on customer needs, size of segment and cost of differentiation.	Client feedback meetings after each project were defined from a strategic pull perspective from project with a dominant formulation in variables on components, process and relationships. Client input varies between projects so that house-building platforms have to be open for non-defined parameters and customized products (Jansson et al. 2013). No direct focus was put on how the platform should develop over time by continuous input from the market even if platform predefinitions were motivated with requirements from client demands and production parameters.
Avoid insisting on total agreement but ask for design solutions that everyone agrees are good enough.	The case study showed a separation between platform development and project improvements. Organisational barriers in a decentralised organisation limit collaboration, which results in different focus on predefinitions. Standardisation of on-site activities was less used in comparison to design activities. All four feedback channels were either push or pull driven, which is difficult to manage in a decentralised organisation. Your point of view without no clear pull could cause information overload instead of creating value for platform improvements (Meiling 2010). Improvements meetings had a clear pull for improvements for the entire supply chain.
Start at top level, iteratively refine to details.	All input is not defined before the project starts and an ETO production has more open parameters than the MTO production. In an MTO context the product platform is refined from the top-level into details (Robertson and Ulrich 1998), while in an ETO context one has to detail the physical system in parallel with defining lower-level functional requirements. Management of constraints and requirements is therefore important for the entire supply chain. By focusing on a detailed component level, purchasing benefits could be reached. Overall costs for the platform must be developed in a cooperative process for the entire supply chain (Robertson and Ulrich 1998). The pull from strategic level to improve the platform in Design Optimisation gives also a push for direct improvements of operational work in projects.
Make process a living one by continuous evaluation and improvements.	Meyer and Lehnerds'(1997) stepwise product development, in figure 3, has proven not applicable in the ETO context for house-building companies. Products releases in the ETO context are not present as in the MTO context because all parameters are not defined when clients enter the design-phase (Jansson et al. 2013a). The process of continuous platform development of activities has been shown to be beneficial for speeding up production by the evaluation of the product offer (Lu et al. 2011). Improvement meetings were the channel that describes a continuous development that involves stakeholders from the entire supply chain.
Evolve the planning process by more members for better understanding.	The supply chain perspective is central for understanding platform standardisation in an ETO context. Contractual and organisational relationships can be standardised for a more efficient process. Collaboration with suppliers does not just need local routines but predefined suggestions and contracts for how to manage relationships with suppliers and sub-contractors. A continuously developed platform needs planning in a combination of strategic expertise and operational experience from users (Bresnen 2004). In the case study, production parameters arose more seldom in experience feedback due to the limited number of sources from on-site work. In order to get feedback from operational work to design and production planning, Gerth et al. (2013) suggests an evaluation of product solutions according to predefined criteria.
Use results to drive the improvement agenda.	In an ETO context separating the design phase from platform development is difficult (Jansson et al. 2013a). Because design work is combined with ordinary production in house-building projects (Winch 2003), evaluation with direct feedback creates a continuous flow. The connection between projects and platform development is central for how house-builders improve standardisation of their platforms (Jansson et al. 2013a). Following Styhre and Gluch's (2010) management of knowledge in stocks and flows, the stocks are the link between the constraints. The case study shows how knowledge flows both from the platform to the project during engineering work, but also in the opposite direction when experience feedback enters the platform, figure 6. In order to create a controllable knowledge flow, experience feedback should be organised in predefined channels with the purpose to cover links between in functional requirements, components, activities, and relationships, which are stored in the platform as knowledge stocks.

The ETO context does not fully follow the MTO development process of platforms presented by Robertson and Ulrich (1998). Based on the current empirical findings, the knowledge flow through text-based channels was focused on components and details in *Your point of view* and *Design optimization*, while *Improvement meetings* and *Client feedback meetings* focus on the process and relationships to improve the platform. A large part of undefined functional requirements before the design-phase means that customers need to iterate non-predefined solutions before they can continue into design. In an ETO context with a partly defined platform (hatched part in figure 5 and figure 6), a focus on feedback improvements following focus on predefinitions results in isolated improvements as opposed to supply chain improvements.

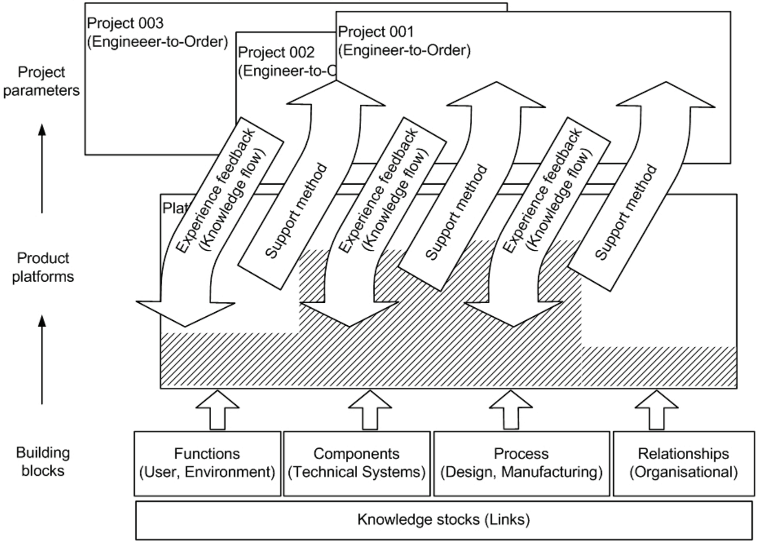

Figure 6. House-building platform with knowledge stocks and flows

With a dominant focus on components and commonalities, purchasing and outsourcing benefits increase but the risk of less total efficiency for the supply chain could inhibit the organisational certainty in platform investments (Karlsson and Sköld 2007). The study shows that a continuous development of platforms is based on small incremental steps of experience feedback from projects. The strength of the project organisation is that it can manage variety together with repetitiveness. Decentralization, the short-term emphasis on project performance and distributed work practices limit improvements (Bresnen et al. 2004). Because the flow varies between projects, a stable process is difficult to achieve and this makes it difficult to plan and evaluate the performance of improvements. In such cases, Imai (1997) suggest that standardisation should follow continuous improvements with small incremental steps. Stabile processes could be defined and a robust system for realising the product is developed.

Discussion

According to Robertson and Ulrich (1998) there are three steps of developing a platform in the MTO context; market positioning, product realisation and manufacturing processes. These are relevant for the house-building supply chain. However, versions of the platform cannot follow from larger renewing stages since the larger part of suppliers, processes and components varies between house-building projects where radical changes in deliveries are replaced or redesigned. In order to form the knowledge flow from projects from previous mistakes to successes (Henderson et al. 2013) experience feedback is one source to develop product platforms. This study only focuses on experience from projects as sources for platform development, but in construction continuous platform development has to be set in the multiple relations of knowledge in a firm (Meiling 2010). In order to create a balance between commonality and distinctiveness, demands have to be set to supply chain standardisation. As an example, a window cannot be standardised as a commonality for purchasing only, but the choice needs to be valued against all functional requirements (client demands, maintenance, regulations), product constraints (other components, physical systems), production constraints (design and manufacturing regulations) and supplier constraints (contracts and relationships). Knowledge between the assets in platform, in figure 5, is the key to manage a partly defined ETO platform. The project organisation has the power to manage non-defined parameters using knowledge stocks in the platform or in people working in the process of house-building realisation (Bresnen et al. 2004).

Long cycle-times for house-building projects generate a long interval between feedback points. The experience feedback in the case shows that direct feedback separated from projects (e.g. *Your point of view*) gives constant data from the supply chain for the improvements of the platform. The study also shows how the company develops their platform over time by using the entire organisation (in a Kaizen approach) in small incremental steps towards a more defined platform. It is relevant to ask if the incremental steps in house-building are enough. Experience feedback is one channel for improving the platform from operational work. Improvements could be due to external factors (e.g. changing markets)and lead to innovations in platform development.

To keep the internal trust for platform investments continuous knowledge flow could use the platform structure to balance commonality to distinctiveness. Platform development needs to improve house-building production with a holistic view of the entire product supply chain to be able to use predefinitions without creating sub-focus on details or create organisational inertia.

Conclusions

The study has shown that a platform constitutes the knowledge stocks in an organisation (Jansson 2013a). Support methods and experience feedback that bring knowledge between a platform and the building project are the knowledge flow. This study has shown the importance of integrating experience feedback for a continuous platform development. In order to achieve economy of scale for platform investments in an ETO context, the development needs to be systematised for the specific context of house-building business and should consider the following conclusions:

- In order to exploit benefits of predefinitions, platform constraints need to be developed with a supply-chain perspective that covers client demands, functional requirements, design parameters, production and supply chain variables.
- The balance between commonality and distinctiveness has to be evaluated against the platform constraints for the entire supply chain.
- Platform constraints (functions, components, processes and relationships) should be developed over time by linking knowledge stocks with knowledge flows in the organisation.
- Clear purpose and direction of feedback channels gives a base for trust in the organisation and decreasing data overflow.
- Channels for experience feedback should have different focus to create feedback not only concerning components, but also processes and relationships.

The interaction between platform managers and operational workers is the out most importance for the development of platform predefinitions. Knowledge flow and storage from day-to-day work have the ability to improve platforms for industrialised house-building but could cause data overflow. Therefore a pull-based knowledge for house-building and related development of platforms is needed in further research.

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PAPER V

Modularization in a housing platform for mass customization

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Proceedings of the 29th Annual ARCOM Conference, September 2-4, 2013
Reading, UK

MODULARIZATION IN A HOUSING PLATFORM FOR MASS CUSTOMIZATION

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The problem of combining production efficiency with flexible product offers in housing design is well known. The platform concept is applied in housing to support design and production with predefined solutions. Modularization can be useful to meet both client demands on flexibility and production requirements on standardisation. To identify the module drivers in housing, ten projects at one off-site housing company were analysed. Furthermore, the cycle time for the modules was recorded. Client, design, purchasing, production and suppliers have different module drivers. When module drivers concur, modules are identified by; identifying clear and few interfaces, the availability of a supplier, and the cycle time for the design and production of the module in relation to the production pace. The results from the case study further show that fixed geometry on modules is a less successful concept than parameterised modules in housing. The ability to outsource technical solutions increased, when the module drivers were combined with a long term relationship with the supplier. Variant modules were successfully applied in the studied company to respond to client demands. Further research is needed on how to configure generic modules.

Keywords: Case study, Engineer-to-order, Housing design, Module drivers, Module identification.

INTRODUCTION

There has been an increasing focus on the platform concept in the construction sector in recent years (Jensen et al. 2012, Thuesen and Hvam 2011). Construction seems to be struggling to balance between the power of flexibility given by project management of complex systems and the efficiency of using standardization of products and processes. The use of platforms, which store product, process and relationship knowledge, develops design and construction work continuously through system innovations (Johnsson 2011, Voordijk 2006). One way of mitigating client demands for variation with supplier requirements on repetitiveness is applying modularization (Baldwin and Clark 2000), where the product is decomposed into modules that constitute 'products-in-products' (Erixon 1998). Successful platform decomposition rests on balancing commonality with distinctiveness i.e. standardization with flexibility. Robertson and Ulrich (1998) argue that costs are driven by commonalities and customer value by distinctiveness. Modularization can complement commonality and distinctiveness if opting to organize the platform with predefined variants to limit the number of unique components and create mass customized products (Hvam et al. 2008). In the creation of modules, different module drivers exist (Erixon 1998), such as the module being a common unit in many designs or a supplier is available.

Construction is identified as one of the largest engineer-to-order (ETO) sectors (Gosling and Naim 2009). In an ETO situation like housing, where the client enters the process somewhere in the design phase, methods that handle uncertainty and client choices for flexibility are useful. Applying modularization in construction has been challenging since client demands tend to require more flexibility than the predefined modules can deliver. A number of investments in standardisation on component level have ended prematurely (Apleberger et al. 2007). Module decomposition could lead to less flexibility vis-à-vis market demands, brand segmentation, and product cannibalisation (Pasche and Sköld 2012). The industry expertise base is wide in housing and the knowledge that firms need to internalise to design and produce complex products is rapidly expanding. Potentially, different actors in the construction supply chain could have different drivers for modularization. The specialist knowledge and drivers that suppliers have is central for individual firms to master when designing complex products (Zirpoli and Becker 2011).

The aim of the research is to meet mass customization by using modularization in a construction supply chain. By analysing module drivers according to platform variants of five technical solutions, module identification was evaluated to the ETO situation. Given the ETO situation, modules in housing cannot always be fully predefined. Therefore, the cycle time for examples of modules in the housing design process was mapped to understand if the design and handling of a module is different from the original definition (Ulrich 1995).

PLATFORMS AND MODULARIZATION

By producing customized goods with low cost, mass customization enables companies to penetrate new markets to capture customers with needs that give them more than standard products (Ericsson and Erixon 2000). In the latest 15 years, housing in Sweden has been striving towards mass customisation using repetition of components and processes in the development of building systems. Companies have organised their effort in product platforms (Meyer and Lehnherd 1997), where component data, process descriptions, relationship conducts, and knowledge creation are stored (Robertson and Ulrich 1998). These assets are either commonalities in the platform, which are repeated in all projects, or distinctive unique parts, that are organised to create variability in products to meet client demands (Thuesen and Hvam 2011). Modules are a subset of the parts in the platform, a collection of parts that can easily be repeated between projects e.g. a balcony solution. Platforms can function without modules, though modules provide a way of predefining variability in the platform and organising the platform for module wise product development.

In an ETO situation, the platform standards and project input parameters are combined during the design phase. This work is made using support methods because the platform can never be fully predefined working ETO (Jansson et al. 2013). One support method is configuration, where predefined modules are configured to a product that fulfils client needs. A drawback with using product platforms is the tendency to favour commonality in physical components, which leads to less product distinction (Karlsson and Sköld 2007). The technical challenge is to create stable interfaces between common and distinctive components (Meyer and Lehnerd 1997). Decomposing the platform into modules is a method to separate and stabilise interfaces, which has been proven useful also in construction (Jensen et al. 2013).

The product architecture is the interrelation between the parts in the platform. Product architecture can be modular or integral. A modular architecture is composed of clearly separable modules where modules and parts solve few functional requirements each (Ulrich 1995). In an integral architecture, one module or part is used to solve many functions. It is therefore more difficult to replace and refine the module separate from the product in an integral architecture.

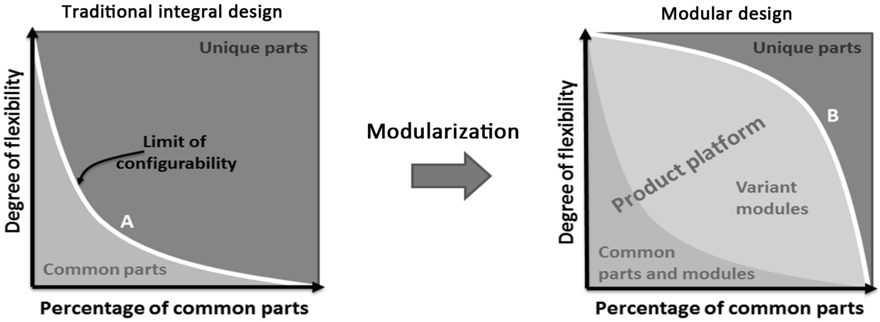

Figure 1. From integral to modular product architecture (Jensen et al. 2013)

In defining modules from unique parts, configurability is enabled with a high percentage of common parts combined with high flexibility, Figure 1, (Jensen et al. 2013). Modularization is to define the boundary between modules with a tight dependency between components inside the module and a loose interdependency between modules. The drivers for modularization differ between stakeholders and they could for the same product define different module boundaries. In a study of product development at Scania trucks twelve generic module drivers were identified by Ericsson and Erixon (2000):

1. Carry-over
2. Technological evolution
3. Planned design changes
4. Technical specifications
5. Styling
6. Common unit
7. Process and/or organisational re-use
8. Separate testing
9. Supplier available
10. Service and maintenance
11. Upgrading
12. Recycling

By using the twelve module drivers in a Module-Indication-Matrix and analyse technical solutions, Ericsson and Erixon (2000) state that the prediction of costs, flow, and production planning was made easier. Because complete modularisation is rarely achieved, interdependency across module interfaces becomes important for how flexible a module is to client demands. The conflict between stakeholder drivers has to be analysed with respect to the manufacturing chain (sales, design, production, maintenance) (Baldwin and Clark 2000).

Long-time relationships with suppliers enable outsourcing of modules and the option to keep core business in-house (Voordijk et al. 2006). By outsourcing the design and production of modules to sub-contractors or suppliers, one can make use of the power of specialists, but with the risk of differing goals and knowledge drain (Zirpoli and Becker 2011). Outsourcing of design, engineering and manufacturing are frequently used in construction as a solution to avoid investments in a large resource-base and to increase the speed in housing production (Lennartsson and Björnfot 2010). Component modularization needs to be communicated with suppliers, production, and engineers so that interfaces and modules yield expected performance of the building (Jensen et al. 2012).

METHOD

The research strategy was to identify a platform at a company where modularization was applied. Thereafter, a case study was performed in four steps: selection of building projects, identification of modules used in the projects, analysis of module repetition within and between projects, and analysis of cycle time for module exit and re-entrance within the construction supply chain. The case study company is a Swedish industrialised housing company, with a turnover of about 70 million Euros per year. The company uses a building system based on prefabricated timber-framed volumetric modules as the load bearing structure for multi-dwelling timber houses. The main process stages include an off-site production phase realised in a factory and an on-site production phase. Average cycle times are 17 weeks for design, 4 weeks for off-site production, and 4 weeks for on-site assembly followed by 6-8 weeks of on-site completion.

The strength of case study research is that the phenomenon is observed by actual practice in its natural setting and therefore could generate and develop new thoughts by meaningful and relevant theory (Voss et al. 2002). The case study gives an opportunity for exploratory investigation of the context of modularization in housing design, and to examine variables for the phenomenon of standardisation that are not all understood (Meredith 1998). Focus is on the degree of independence of modules, module interfaces and module drivers in relation to long term relationships to a number of external suppliers that deliver the studied modules: stairs, façades, foundation, balconies, and bathroom floors.

Observations of the design team have been made continuously by the authors to follow the use of platform standardisation in projects to see how stakeholder requirements and drivers cause variations in the product standard. Log book notes from building projects, drawings from building projects and documentation of product standards were used as core data and to verify observations applying a multi-methods perspective (Voss et al. 2002). To find module drivers and their weight for different technical solutions, structured interviews with one salesperson, two engineers, one production manager, and one supplier were conducted focusing ten building projects from 2012. Both tenancy and condominium projects with a living space from 2000 m2 to 8000 m2 were chosen to represent the client requirements the case company has to manage.

Analysis has been done to identify how the decomposition of modules was practiced, and to identify a modular or integral architecture. The module drivers for different stakeholders were identified and organised according to Eriksson's Module Indication Matrix. The cycle times for different modules were established by studying planned and actual cycle times in the ten projects.

CASE STUDY RESULTS AND ANALYSES

The platform is documented through rules and recommendations for design, purchasing, and production. The documentation of product standards focus component interfaces in the platform and recommends certain dimensions and production processes to be static between projects.

Modules

Bathroom floor

The case study company has together with a supplier developed a bathroom floor that is based on a glass-fibre reinforced sandwich construction with integrated drainage gutter and sleeves for toilet and sink. The underlying drivers for development of the bathroom floor were functional and legal requirements regarding moisture safety. The solution can have different types of finishing (tiles, carpet, and floor heating). Module drivers for developing the bathroom floor were to offer a moisture proof system with clearly defined interfaces that enable supplier production operations. Furthermore, a decrease in cycle time was sought, since the former solution encompassed curing times of several hours. The 6 predefined shapes of bathrooms with 24 dimensions in the platform were an enabler for efficient purchasing from external suppliers in batches, table 1. For the supplier, module repetition meant time savings in setup and production planning. Clients have demands on the interior finishing in their bathroom, but seldom require specific dimensions except for accessibility for the disabled. Using prefabricated bathroom floors, and organizing tiling off the production line saved a curing time of about 6 hours. As input, information about floor type, amount, delivery time, and finishing must be communicated to the supplier 14 weeks before production assembly starts in the factory.

Balcony

Prefabricated balconies have been developed following the same technical concept as the bathroom floor, with a glass-fibre coated massive timber slab hanging on steel tie rods secured to the outer wall. The underlying driver for developing the balcony system was to offer a light-weight solution without outer load bearing columns to meet aesthetical requirements. The driver from a design perspective was to repeat the interfaces (the tie rod and fixtures) while keeping the scalability in dimensions i.e. a parameterised solution. From a purchasing perspective, the repetitiveness enables easier purchase orders with 3 geometrical variants specified in the platform, table 1. The driver for modularization at the supplier was to find repetitiveness over projects for set up, production, and configuration of their production. Client requirements are posed on style, ease of use, safety in the railings, and ease of maintenance. The design of the balconies is decided late in the sales process; wherefrom the production flow is separated to the supplier and re-joined at the building site, figure 2.

Façade

Façade systems are separated from the structural system and can be varied between the shape of boards, bricks, plastered, vertical and horizontal wooden façades, table 1. Aesthetical client requests have been the underlying driver for standardisation of façades. Interface standardisation has been in focus, including the interface to the structural system, to the balcony, to the foundation, to openings, and to fixtures in the façade. The interfaces are realised partly in factory production, partly in on-site production. Suppliers mount the façade in the case of a plastered or brick façade, otherwise the case company mounts the board and wooden façade themselves. If using a sub-contractor, they need to provide a warranty for their work and have to meet same pace requirements as the case company staff. The façade is the most disconnected module of the studied ones with unique geometrical solutions in studied projects. Already in the sales phase information is available to set up a subcontract with a supplier that fulfils the work during on-site completion, figure 2.

Foundation

Foundation works are most often sub-contracted using local firms for the specific site. Rules and tolerances for the foundation are stored in the platform and a time schedule is made to meet the production pace both off-site and on-site. The foundation module needs to meet tolerance requirements and loading requirements from the superstructure, as well as interface requirements from the façade, the stairwell, the service shaft, and the services connections. The case study firm often has the upper foundation surface as the contract boundary. Therefore, the properties both in dimensions and in concrete moisture content are strictly regulated in the sub-contract. Drivers for making the foundation a module is the lack of capacity and knowledge at the company to perform foundation works that are complicated. Information from sales and design are critical from a flow perspective, making foundation design the top priority in the early design phase, figure 2. The average cycle time needs to be about 18 weeks output from design to completion of foundation to conform to the production pace.

Table 1.Module variants in platform and customization in ten building projects

Technical solutions	Production variants in platform (customized)	Shape variants in platform (customized)	Geometrical variants in platform (customized)	External interfaces
Bathroom floors (modular)	prefab (crafts made)	6 (2 shapes)	24 (8 unique of 634)	Few (<10), Fixed
Balconies (modular)	prefab (crafts made)	6 (1 shape)	3 (58 unique of 375)	Few (<10), Fixed
Façades (modular)	board, brick, plastered, wooden (none)	5 (0 shape)	0 (all unique)	Many (>10), Fixed
Foundation (integral)	slab, basement (none)	0 (1 shape)	0 (26 unique of 56)	Many (>10), Tailored
Stairs (integral)	steel (timber)	5 (5 shapes)	0 (42 unique of 183)	Few (<10), Tailored

Stairs

The company has chosen to use steel stairs in their housing platform. The underlying driver for the limitation of structural stair material was to be able to offer a solution that resists abrasion, vibrations and fire, while being light-weight, tolerance stable, and possible to prefabricate. Drivers for standardising the stairs in the company were to develop solutions that have flexibility in meeting client demands on abrasion materials. Furthermore, the production pace was crucial, ruling out stairs that are assembled on-site. With the shortest lead time from design to completion (8-10 weeks), it was imperative to arrive at a standardised module that fulfils all requirements, can be designed swiftly, and offers enough distinctiveness (e.g. the width ranges from 856 mm to 1200 mm founding the need for a parameterised module). The supplier driver for modularization was the repetition in projects enabling configuration of production robots, tool jigs and instructions. While standardising the step surface, on-site production put requirements on handling, where 5 shapes were stored in the platform and repetition in projects on 42 unique of total of 183 stairs, table 1.

Module drivers

In figure 2, the cycle time for the suppliers is displayed in relation to the overall building process at the case study company. Figure 2 shows that the shortest cycle time is given the stair supplier, while the longest applies to the façade sub-contractor. The modules differ in information content needed from sales and design. Stairs and bathroom floors need much information from design as these modules are immersed into the building, thus they become critical time wise both for the supplier and the case company. The balcony system with few interfaces to other systems and a long cycle time is easier to handle. The façade system does not need any design and therefore the sub-contractor for facades can plan their work over long periods of time. Foundations works are the most critical in the early phases of design as they not only are subcontracted and involve quite long curing periods for the concrete, but also as they need to be finished before on-site production starts.

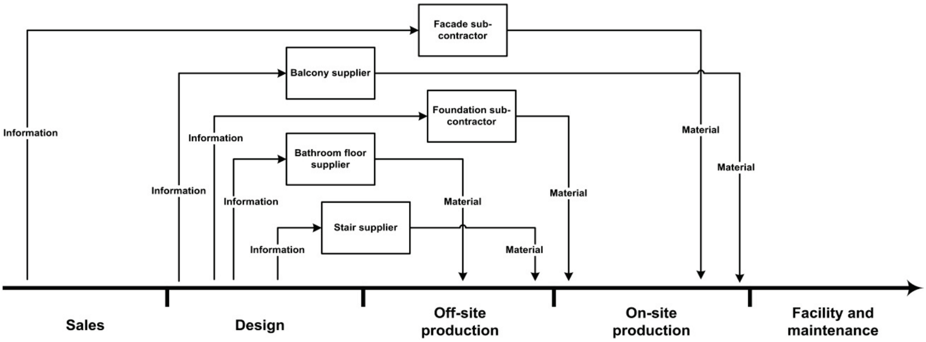

Figure 2. Parallel supplier and sub-contractor processes for the five studied sub-systems following the building process at the case company.

By the analyse using the Module Indication Matrix client drivers for Styling, Service and maintenance varies between technical solutions. Client drivers for modularization are, according to the interviews with sales personnel, related to a price perspective, which is why the first column in table 2 has been subdivided in private, public, and developer clients. Private clients, that develop houses for their own organisation to sublet, focus on economy, customer satisfaction through style, and functionality in internal equipment. They have fewer demands on repetition but wants specified choices. Public clients have higher demands on service and maintenance than private clients and pose demands on durable façades and granite laid steps in stairs expressing maintenance proficiency. Project developers have a short-term customer focus with high demands on styling and function for selling condominiums quickly resulting in weak and few drivers for client modularization, table 2. Technical specifications have drivers from al type of clients for functional requirements for moisture and structural stability on Bathroom floor, Balconies and facades.

The case company has to match the pace of production with client demands, which makes speed a prominent driver for modularization. Other case company drivers were carry-over between projects and common units inside projects, prominently for bathroom floor and balconies. Work process re-use is practiced in production for the modules, where the interfaces are similar although the components differ in size. Balconies, façades and foundation are all assembled on site with 2-3 variants of reusable processes. Off-site production was applied for the façades in 6 of the 10 studied projects. The interfaces are a shared responsibility between factory production, on-site production and external suppliers making it important to have a process owner to avoid sub-optimisation. Balconies and bathroom floors have a large amount of pre-defined parameters in the case company platform. The case company has long-time relations with these suppliers and the modules have few and standardised interfaces to other technical solutions.

Table 2. Stakeholder drivers using the Module Indication Matrix (Ericsson and Erixon 2000).

Module drivers *Technical solutions*	*Client (Private, Public, Developers)*	*Design/Purchasing*	*Production*	*Supplier/Sub-Contractor*
Bathroom floors	*4.Technical specifications* ●●● *5.Styling* ●○● *10.Service and maintenance* ◐●○	*1.Carry-over* ● *2.Technological evolution* ● *4.Technical specifications* ◐ *6.Common unit* ●	*1.Carry-over* ● *2.Technological evolution* ● *4.Technical specifications* ● *6.Common unit* ○ *7.Process and/or organisational re-use* ● *8.Separate testing* ●	*1.Carry-over* ● *2.Technological evolution* ● *4.Technical specifications* ○ *6.Common unit* ● *7.Process and/or org. re-use* ●
Balconies	*4.Technical specifications* ○○○ *5.Styling* ●●● *10.Service and maintenance* ◐●○	*1.Carry-over* ● *2.Technological evolution* ● *3.Planned design changes* ◐ *4.Technical specifications* ● *6.Common unit* ●	*1.Carry-over* ● *2.Technological evolution* ◐ *4.Technical specifications* ● *6.Common unit* ○ *7.Process and/or organisational re-use* ○ *8.Separate testing* ●	*1.Carry-over* ● *2.Technological evolution* ● *4.Technical specifications* ● *6.Common unit* ● *7.Process and/or org re-use* ●
Façades	*4.Technical specifications* ●●○	*2.Technological evolution* ● *4.Technical specifications* ●	*1.Carry-over* ● *2.Technological evolution* ◐ *4.Technical specifications* ◐ *6.Common unit* ◐ *7.Process and/or org. re-use* ● *8.Separate testing* ●	*1.Carry-over* ◐ *2.Technological evolution* ● *4.Technical specification* ● *7.Process and/or org. re-use* ●
Foundation	*4.Technical specifications* ○○○	*2.Technological evolution* ○ *3.Planned design changes* ○ *4.Technical specifications* ●	*4.Technical specifications* ○ *7.Process and/or org. re-use* ●	*4.Technical specifications* ● *7.Process and/or org. re-use* ●
Stairs	*10.Service and maintenance* ◐●○ *5.Styling* ●○●	*3.Planned design changes* ● *4.Technical specifications* ● *6.Common unit* ●	*4.Technical specifications* ○ *7.Process and/or org. re-use* ○	*1.Carry-over* ● *4.Technical specifications* ◐ *6.Common unit* ● *7.Process and/or org. re-use* ●

● *= strong driver* ◐ *= medium driver* ○ *= weak driver*

Supplier drivers for modularization are related to gaining repetition in the production through carry-over, technical specification and process and organisational re-use for all technical solutions in formwork, machine setting and production preparation. Suppliers and sub-contractors are depended on where in the process they get information from the main process about dimensions, choices, finishing, etc.

Modular or integral architecture

Many similar strong module drivers, table 2, for bathroom floor and balconies have led to a modular architecture (Ericsson and Erixon, 2000) and a long-term development together with suppliers. Stairs are another structure with an opportunity to become a module. They are still an integral architecture in the platform, due to many tailored interfaces, varied drivers from stakeholders and a short time relationship with the supplier. Foundation works seen as a module has few and weak drivers, but is still a module due to its early separation from the production flow. Façades are a modular solution to create the outer climate shell for the building and is to a large extent independent from the platform apart from interfaces around openings in the façade. The number of different façade shapes is 5, which makes the definition of interfaces a viable task.

Modularization of housing platform

Components with a modular architecture are easier to standardise due to few number of interfaces with the rest of the platform (Voordijk et al. 2006). Some of the modules in the case study have been outsourced since long time relationships with suppliers. Façades and foundation have specialised suppliers providing the module and they work as subcontractors for many contractors. Two modules in the case study were created by the case study company in cooperation with small firms. The module drivers displayed in table 2, visualises the driving forces behind the modularization. The co-creation of the modules led to the smaller firms growing to become suppliers, at first to the case study company, but during later years also to other contractors. The stair module is in the case study identified as the possible next module to be outsourced due to some strong module drivers but especially to the few interfaces, table 2.

A risk with modularization is that it might lead to a focus on constructability instead of functionality for the client (Voordijk et al. 2006), which also must be focused when module drivers are analysed. The modularization in housing for platform use seems more dependent on shape and materials than on geometry, table 1. Thus, the case study shows that modules in housing seemingly need to use parameterisation as opposed to having a fixed geometry.

CONCLUSIONS

To meet mass customisation in housing platforms, where repetition is low and customisation is high, the findings in this paper suggests:

- Modularization is useful if the modules are parameterised as opposed to having a fixed geometry.
- For modularization to succeed there needs to be module drivers not only for the contractor and suppliers, but also for the clients.
- Different from modularization made in e.g. the automotive industry, modularization in housing needs to incorporate the cycle time in the engineering phase as modules are made to order i.e. not off-the-shelf products. Possibly this indicates that not only the supplier availability is a module driver in housing, but also the supplier cycle time.
- Modules in housing can provide both commonality and distinctiveness by the use of a partly defined platform.

Variant modules were successfully applied in the studied company to meet client demands, but need further research in configuring generic modules for the entire supply chain.

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APPENDICES

Appendix 1:

- *Interview questions - Industrialised house building design process (Study 1.)*
- *Interview questions - Support systems for industrialised house-building design (Study 2.)*
- *Interviews - Platform development using experience feedback (Study 3.)*
- *Interviews - Platform development by modularization (Study 4.)*

Interview questions - *Industrialised house-building design process* (Study 1.)

The purpose of the interviews is to collect a general picture of the design process at Lindbäcks. Interviewed respondents for Study 1 are; Factory Manager, Project Manager , Sales Manager, Consultant Coordinator, Structural Engineer 1, Structural Engineer 2, HVAC Engineer. According to secretes will all answers be managed confidentially. No names or related citations will be published without respondents agree.

Introductory questions (to all)

1. What is the core business in the company?
2. How is the company organised?
3. Tell me about your role at the company?

Open-ended questions (to all)

1. Could you describe the entire process, from sales to delivery and maintenance?
2. Could you describe the design process?
3. How long time takes it from signed contract to production start in factory?
4. How do planning and follow-up works? Describe tools and methods.
5. What kind of deadlines and meetings does the process involve?
6. Define critical moments for the design process and describe these?
7. Do you have some guiding that you follow through design?
8. What specific stages in housing design need specific planning?

Specific questions first round.

1. Why do your company need a more efficient design process? (to Factory Manager)
2. What is the contribution of external and internal resources? (to Factory Manager, Consultant Coordinator)
3. How is information shared between actors in the design process? (to Factory Manager, Project Manager, Structural Engineer 2)
4. How is ICT-tools and system used in the design process? (to Factory Manager, Structural Engineer 1 and 2, HVAC Engineer)
5. What type of software is used for planning, drawing and management? (to Factory Manager, Project Manager, Structural Engineer 2)
6. What type of deliveries is done in process? (to all)
7. In creating deliveries in form of drawings and documents, what type of activities are necessary in design and do you have general titles for each activity?
(to Structural Engineer 1 and 2, HVAC Engineer, Consultant Coordinator)
8. How do you communicate choices with customers both before and after signed contract?
(to Sales Manager and Project Manager)
9. How is choices stored and handled in design after signed contract? (to Sales Manager and Project Manager)

Specific questions second round.

1. For activities in design, could you estimate how many hours are spent on each activity? (Project Manager, Structural Engineer 1)
2. Who are recipients of information deliveries from design? (to Factory Manager, Project Manager, Structural Engineer 1)
3. What type of format are specific deliveries in; files, paper documents, mail, etc.? (to Project Manager, Structural Engineer 1)
4. How is coordination made between internal and external consultants to control project progress? (to Factory Manager, Project Manager, Structural Engineer 1)
5. Tell me about the process to prepare deliveries just before production start? (Structural Engineer 1)

Interview questions - *Support systems for industrialised house-building design* (Study 2.)

The purpose of the study is to collect and complement data from NCC and Lindbäcks for platform use and related support methods in design work.

Interviews to development (strategic) staff – *Platform use by process support*

Interviewed respondents at management level for Study 2 are; Platform Manager 1, Platform Manager 2, Business Manager 1, Business Manager 2 at NCC and Platform Manager at Lindbäcks.

According to secretes will all answers be managed confidentially. No names or related citations will be published without respondents agree.

Open-ended questions about *design processes* (NCC)

1. Tell me briefly about your position and related work at NCC?

2. Describe how housing design processes with whole process commitment are done from a historical perspective?

3. Describe the new implemented design work and differences from the traditional?

4. How is the goal with the changed design process strategy formulated?

5. How can the new strategy improve efficiency to design work?

6. How important is it to decrease time to delivery?

7. How can the new strategy improve effectiveness in design deliveries?

8. How important is it to improve the review process for deliveries?

Conceptual defining of *platform use* (to all)

1. Describe how the platform is systemised in documents and IT-systems?

2. How is the use of the platform described according to physical components and process related use?

3. What is the aim of using platforms in housing design?

4. Who is getting the benefits of using the platform?

5. What are the greatest benefits of using the platform for you?

6. When in the process is the platform used most frequently?

7. Could you see any demands in how to visualise the platform, in case how?

8. How are design and production processes connected to platform standards?

9. Is it clear how to use the platform before the start of a project?

Conceptual defining of support methods complementing *platform use*

1. Describe how support methods that are suggested to be used in design with the platform?

2. How do this methods support different stages in design?

3. Who is getting the benefits of using these support methods?

4. What are the greatest benefits for you of using these methods?

5. How could improvements of the platform replace these support methods?

6. When in the process is these methods used most frequently?

7. How are design and production processes supported by these methods?

8. Is it clear how to use these methods before the start of a project?

Interview to project (operational) staff – *Platform use by process support*

Interviewed respondents at project level for Study 2 are; Project Manager 1, Project Manager 2, Structural Engineer 1, Structural Engineer 2, Energy Engineer.

According to secretes will all answers be managed confidentially. No names or related citations will be published without respondents agree.

Open-ended questions about *design processes* (NCC staff)

1. Tell me briefly about your position and related work at NCC?
2. Describe how housing design processes with whole process commitment are done from a historical perspective?
3. Describe the new implemented design work and differences from the traditional?
4. How is the goal with the changed design process strategy implemented?
5. How can the new strategy improve efficiency to design work?
6. What kind of parameters could decrease time to delivery?
7. How can the new strategy improve effectiveness in design deliveries?
8. How could the review process be improved for deliveries?

Conceptual defining of *platform use* (to all except the energy engineer)

1. Describe shortly how the platform is systemised in documents and IT-systems?
2. How is the use of the platform described for engineers/project managers?
3. How do you use platform standards in housing projects?
4. Who is getting the benefits of using the platform?
5. What are the greatest benefits of using these methods for you?
6. When in the process is the platform used most frequently?
7. Could you see any demands in how to visualise the platform, in case how?
8. How are design and production processes connected to platform standards?
9. Is it clear how to use the platform before you start a project?

Conceptual defining of *support methods* complementing platform use (to all except the energy engineer)

1. Describe shortly what type of support methods you use in design with the platform?
2. How do this methods support different stages in design?
3. Who is getting the benefits of using the platform?
4. What are the greatest benefits of using these methods for you?
5. How could improvements of the platform replace these support methods?
6. When in the process is these methods used most frequently?
7. How are design and production processes supported by these methods?
8. Is it clear how to use these methods before you start a project?

Open-ended questions about *energy design processes* (to the energy engineer)

1. Describe shortly the analysis of energy through the design process?
2. Describe how alternative design solutions are used through the process?
3. How is requirements logged or visualised through the design process?
4. How is software used according to phases in design?
5. Describe involvement of energy analysis through design.
6. In the project, how many hours did you spend by energy analysis?
7. How can the visualisation of requirements improve energy design, if yes how?

Interviews - *Platform development using experience feedback* (Study 3.)

The purpose of the study is to collect and complement data from NCC how continuous platform development is done in projects but also the planned strategy of developing experience feedback.

Interviews to development (strategic) staff – Platform use by process support

Interviewed respondents at management level for Study 3 are; Platform Manager 1 (Building system), Platform Manager 2 (Building system), Platform Manager 3 (Process system), Platform Manager 4 (Information system).

According to secretes will all answers be managed confidentially. No names or related citations will be published without respondents agree.

Open-ended questions about *experience feedback* (to all)

1. Tell me briefly about your position and work at NCC?
2. Describe how the housing platform develops continuously?
3. Describe used experience feedback method and their purpose?
4. How is each experience feedback method managed in the organisation?
5. How is each experience feedback method developed to support platform use?
6. How can these methods be developed to better manage experience for the development of your organisation?
7. How do you measure results of using platform?
8. How do you measure result of experience feedback?

Interviews - *Platform development by modularization* (Study 4.)

The purpose of the study is to collect and complement data from Lindbäcks how module identification and modularization could develop platforms. Because the study is done in a multi-method perspective by a combination of observation, documented platform and last interviews, structured design of questions to the each specific topic is selected.

Interviews to development (strategic) staff – Platform use by process support

Interviewed respondents at strategic level for Study 4 are; Sales manager, Structural engineer 1, Structural engineer 2, Production manager, and one supplier (balcony and bathroom floor) were chosen.

According to secretes will all answers be managed confidentially. No names or related citations will be published without respondents agree.

Structured questions about *modularization* (separated to specific component/sub-system)

1. Tell me briefly about your position and related work at Lindbäcks?
2. Describe the process of design and manufacturing of bathroom floors?
3. Describe the process of design and manufacturing of balconies?
4. Describe the process of design and manufacturing of façades?
5. Describe the process of design and manufacturing of stairs?
6. Describe the process of design and manufacturing of foundation?
7. Describe the demands for variability for each component/sub-system?
8. Describe the demands for repetition for each component/sub-system?
9. How is this demands connected to different stakeholders both in sales, design, manufacturing and maintenance? Could you describe for each component/subsystem?

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