PRODUCT DEVELOPMENT THROUGH LEAN DESIGN AND MODULARIZATION PRINCIPLES

Patrik Jensen [1], Emile Hamon[2] and Thomas Olofsson[3]

ABSTRACT

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

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

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

KEY WORDS

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

INTRODUCTION

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

[1] M.Sc., Div. Construction Engineering and Management, Luleå university of Technology, Sweden, Phone +46 8 566 414 61 , FAX +46 8 566 410 50, patrik.jensen@tyrens.se

[2] M.Sc., Tyréns AB, 205 19 Malmö, Sweden, Phone +46 8 566 416 68 , FAX +46 8 566 410 50, Emile.Hamon@tyrens.se

[3] Professor, Div. Construction Engineering and Management, Luleå university of Technology, Sweden, Phone +46 920 491362, FAX +46 920 491091, Thomas.olofsson@ltu.se

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

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

OBJECTIVES, AIM AND METHOD

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

THEORY

LEAN PRINCIPLES AND BUILDING SYSTEMS

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

By standardizing both the building parts and the production processes, Lean principles can reduce variation, and minimize waste (Morgan and Liker 2006). The prefabrication and production of construction components under controlled conditions in a factory plant can reduce complexity and variation in the construction process (Höök and Stehn 2005). Björnfot and Stehn (2008) also argue that the standardization of the building components will in the long run provide the benefits in the building process. This argument emphasizes that a building system not only consists of a technical platform, but also a platform of processes that delivers the final product to customers. Lessing (2005) defines a building system consisting of a development phase and a configuration phase, see figure 1. The development phase includes the development of a technical and process platform. The platforms will then be used in the configuration phase adapting the building system in the specific construction project. The generic platforms (technical and process) can be continuously improved (Kaizen) through lessons learned in the configuration and production of the individual projects. The feedback will provide information that can be used to enhance the flexibility of building system and avoid ad-hoc solutions to solve the problems caused by adaption to customer demands (Womack and Jones 1990).

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

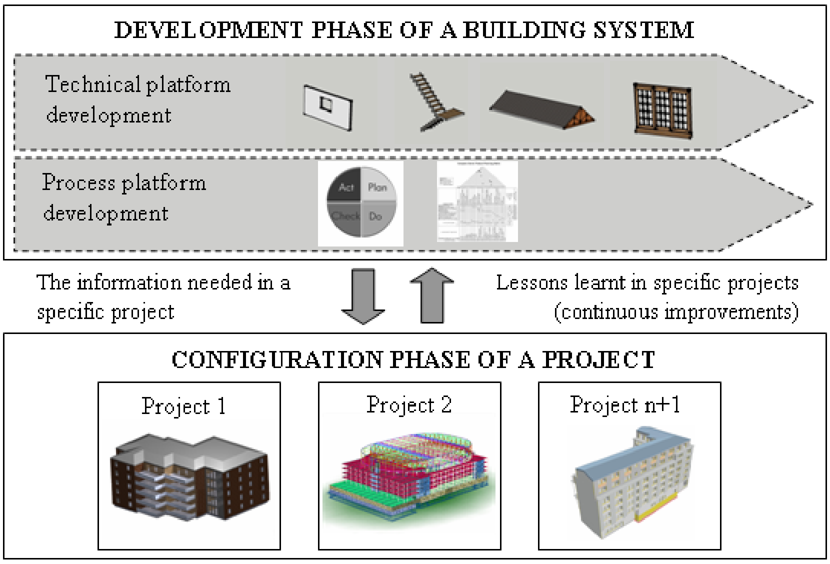

Figure 1: Industrialized housing process (adapted from Lessing, 2006)

MODULARIZATION AND CONFIGURATION

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

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

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

CASE STUDY: THE DEVELOPMENT OF A BUILDING SYSTEM

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

DEVELOPMENT PROCESS

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

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

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

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

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

TECHNICAL PLATFORM

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

	Phase 1: Walls	Design Parameters/ input																				
Discipline	**Functional Requirements** Architects [A], structural design engineers [SE], clients [C], construction site managers [SM], managers in factory [FM], process engineers [PE]	**Degree of importance**	Resist shear forces (low medium high)	Fire resistant load bearing walls (90 minutes)	Vertical load bearing (low medium high) forces	Less then 0,3l/min draft	More then 300mm thick insulation	Possible to alter length of wall	Acoustic in apartment not less then class B	Separated apartments	Separated finishes from load bearing structure	Separated installations from load bearing structure	No load bearing walls between rooms in apartment	Maintenance cost less then (xx dollar/year)	Optional to place (doors, windows etc)	Possible to have window openings of 2m	No load bearing walls between apartments	Modularized to system	Standardized connections between modules	No elements longer then 8m	Built in a tent	Possible to stack modules beside each other
A	Flexible to master plan	a						x							x	o	o					
A	Possible to choose installation location	c									o	x										
A	Hidden installations	c									o	x										
A	Possible to have large window openings	b													o	x						
A	Large windows close to balcony	b													x	x						
A	Flexible to alter floor plan after built	b						(o)			o		x				x					
A	Possible to have different floor plans vertically	a											o				x					
A	Alternative finishes outside	a									x				o							
A	Alternative finishes inside	a									x				o							
SE	Horizontal stabilizing	a	x	x																		
SE	Vertical load bearing	a		x	x																	
SE	Fire resistant for buildings up to 8 floors	a		x																		
SE	Noise reducing between apartments	b							x	x							o					
SE	Climate protecting	b				x	x															
SE	Wind resistant	a				x																
C	Low energy consumption	b				x	x															
C	Cost efficient constructing	a																x	o			o
C	Cost efficient living	b					x							x								
FM	Simple production process	a																x	x			
FM	Same building techniques used earlier in	b																x				
SM	Short onsite assembly time	a																	x		o	
SM	No contact with water during site assembly	a																			x	
SM	Able to be built of site	a																		x		
PE	Easy to deliver on time	b																				x
PE	Delivered with as few lories as possible	c																				x
PE	Easy to assembly on site	a																	x	o		
	x = Strong Relationship																					
	o = Medium Relationship																					
	(o)= Low Relationship																					

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

The building system is based on a design grid of 150 mm to give the production system greater and better use of materials, and reduce the possible solution space. The same technique was used in an early modular building system where Brooks (2005) defines a key part of the technical platform, with the use of a planning grid enabling the plan to change size and shape at any point of the grid. The production system that will produce the developed modules for the multistory timber house building system is an existing factory producing elements used in single housing projects. Therefore in the development of the technical platform, the production constraints were already given and had to be integrated in the design of the new system. Since the production constraints were imposed by the existing production facility, the manufacturing process of sub-assemblies was given. If a new production system facility would have been developed, solutions like "walls in walls" could have been developed and implemented with shorter lead time as a result. Many of the modules that have been developed have the function of "cut to fit" modularity such as the framing of joists. Another example is the "stabilization wall" that consists of 3 types: Type A, B and C. The only difference between the different types is the shear capacity. The interfaces are the same and the connections between them are dimensioned for the highest load. Thus, in a configured project some walls will be oversized and stronger than they need to be. Here, a better production system can be developed to lower the total production costs (Gerth 2008). However, this will also be a question of the balance between investments in a new production system versus how these costs can be depreciated over time.

THE CONFIGURATION PHASE OF A PROJECT

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

- **Customer view** **-** Configuration of the project
- **Engineering view** **-** Control, verifying the systems constrains
- **Preproduction part view** **-** Manufacturing drawings, CNC-code generation
- **Site view** **-** Assembly drawings, scheduling and site-plans

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

When the architect has configured the project, the engineering department needs to check that the configured design is according to the system rules and that the design fulfills the requirements, such as wind and snow loads and energy consumption imposed by the customer, local and national regulations and the location of the final building. Especially in the development of new building systems, configurations that have not been tested need to be verified (Gerth 2008). This step will most likely diminish as more configurations are tested and the configuration tool continues to develop. After the customization of the project is checked and the client is satisfied with the result, the production drawings and output for the manufacturing process is produced. Here the introduction of design tools used in the manufacturing industries is recommended. The manufacturing industry has for many years worked with parameterization and modularization and these tools are more advanced and adapted to support the manufacturing and assembly process. In figure 3, this is described as the preproduction part view and the use of parameterized configurable modules will greatly enhance the information flow. When the modules such as walls and "framing of joists" have been built in a prefabrication factory they need to be assembled at the building site. In order to create an efficient work flow on site the use of Last Planner System (LPS) (Ballard 1994) is recommended. The use of the CAD - model made by the architect can be used in describing the Site view. LPS provides a systematic framework for planning and control of the work flow on-site. Using the Lookahead planning together with the seven prerequisites makes tasks ready to be executed efficiently, eliminating waste in the assembly process.

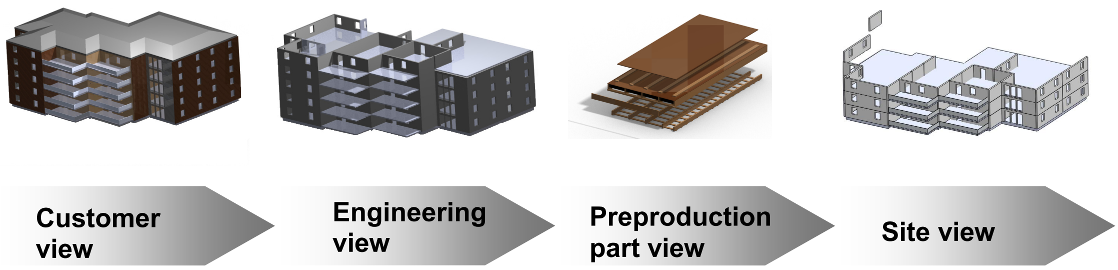

Figure 3: The Configured Product Described in Different Views

DISCUSSION CONCLUSION

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

The technical platform described in the paper is based on the same modularization principles used in the manufacturing industries. The similarity between the building system and product platforms used in e.g. the Scania's production system is evident. Scania configures their trucks by assembling different kinds of modules to fulfil the customer requirements. These modules can be produced separate from the specific truck but the modules and components used in the truck can be produced on forecast from the sales office. This approach is used in the building system but the decoupling point of the building system (modules and components that the wall consists of, not the whole building process) is earlier in the supply chain. The reason for producing less before the specific project assembly is due to the fact that the production factory is already operating and producing wall elements for the single housing market in Sweden. In the configuration phase of a project, the process consists of a design phase, defined in the customer view constrained by the rules of the building system. To facilitate the introduction of new building systems on the market, the configuration tools need to be integrated in the design tools used by the architect. The tools have to be able to generate rendered views of the project that the designer is familiar to. The only restriction is that it needs to be object oriented to support definition of the constraints that are put on the design by the building system. The generation of drawings and output to Computer Numeric Control (CNC) machinery in construction applications are generally less developed than mechanical applications. Configuration tools used in the mechanical industry have been working with parameterization longer and also have connection to Product Data Manager (PDM) and Product Lifecycle Manager (PLM) systems that will probably host the building systems of the future. These systems also have version control and change management support.

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

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