CONFIGURATION AND DESIGN AUTOMATION OF INDUSTRIALISED BUILDING SYSTEMS

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ABSTRACT

Construction companies in Sweden have for many years been moving work from site to factories, especially in the timber housing industry. These factories are also installing more and more automated production lines calling for better integration between design and production. So far, design tools in the construction industry have often been developed without possibility of parameterization, design automation or connections to Computer Numeric Control (CNC). Much of recent research has also been focused on improving the information flow in the traditional building process due to the lack of integration with other tools used by different disciplines. Also, constraints imposed by developed building systems cannot not be easily transferred 'upstream' the design process.

This paper aims to investigate the management of information flow between architects, engineering and production in the design of industrialized building systems. Furthermore, the possibilities of parameterization and design automation is investigated for the implementation of rules and constraints imposed by the building system in design tools used by architects and engineers with the purpose of reducing non-compatible design solutions and to integrate the information flow with the engineering and production process. First, building systems are classified according to customer order decoupling point in the product specification process. Building systems classified as configure-to-order or select-variant are suitable candidates for implementing configuration systems. Then, the information flow is demonstrated in the configuration of a timber floor slab. It is concluded that the engineering design can be automated to a large extent using configuration tools if the architectural design obey the rules imposed by the building system. Also, the amount of data transferred between architect and engineer is reduced since much of the information and knowledge is transferred into formal computer interpretable knowledge.

Keywords: Building system, design automation, information flow, parameterization and constraint based design

1 INTRODUCTION

As in other western countries, (Teichholz 2001, Latham 1994, Egan 1998), the construction industry in Sweden has been accused for low productivity and the Government has set up public investigations scrutinizing said industry, (SOU 2002:115). The Swedish construction industry has replied by launching systems for building multi-family houses, hereafter referred to as building system, in an attempt to make the construction process more efficient.

Factory (prefabrication) processes and lean production concepts have successfully been adopted in Japan (Gann, 1996). Also, approximately 74% (between 1990 and 2002) of the detached single houses are manufactured in permanent factories in Sweden. From a market point of view, this indicates that a traditional manufacturing approach could have potential for the whole housing industry, (Bergström and Stehn, 2005). One distinct difference between the detached single-house market and the production of multi-storey houses is the way business is organized. Turnkey forms of contract including responsibilities to fulfil performance requirements to end users predominate the detached single house market while design-bid-build or design-build contracts between actors in the project and the professional client representing the end user are common in multi-dwelling housing projects.

New building systems have been introduced by construction companies on the Swedish market in the last decade (Andersson et al 2009). However, a serious obstacle for the successful introduction is the possibility to configure the building according to project requirements considering the constraints imposed by the building systems (Jensen 2010). The traditional design-bid-build project often leads to requirements on technical solutions violating the rules of building system. This kind of ad-hoc customization are common and can in the worst case be more costly to perform than a traditional on-site construction project (Andersson et al 2009, Jensen 2010).

The objective of our research is therefore to develop a theory from which industrialized builders can select a strategy regarding product development and project customization of building system.

2 THEORY

2.1 Building systems

Building system for industrialized construction is defined as the collected experience and knowledge in how to realize a construction project (Söderholm, 2010). Thus, a building system can be standardized both in technical solutions and in standardized work. The industrialized house-building process according Lessing (2006), consists of the development and configuration of a building system. The building system includes both a technical and a process platform. The building system is then configured adapting the developed technical and process solutions to the specific building project. The idea is to continuously improve the building system through lessons learned from configuration and production of individual projects and develop new improved versions. The shift from unique “on-of-a-kind” building projects to a more manufacturing process and product centric approach is believed to increase the productivity in the industry. However, the demands for standardization from a production point of view need to be balanced by the demand for customization. Manufacturing industries have developed new methods and design processes combining customers’ requirements for customization and at the same time fulfilling the need for standardization of the production process (Pine 1993; Hvam et al. 2008).

2.2 Customer order decoupling point

Make-to-stock, assemble-to-order, make-to-order, engineer-to-order are distinctions in traditional manufacturing to differentiate how “deep in” or up-streams, in the design and manufacturing process the customer order determines the actual production. In traditional manufacturing the decoupling point is the boundary between make-to-order and make-to-stock. Modularization and standardization of semi-manufactured items have been ways to increase efficiency and lower costs in production, decreasing delivery times, and even increasing the flexibility and variety of products to satisfy customers’ demands. Christopher (2001) discusses the introduction of a strategic inventory to hold common sub-assemblies and only complete the final assembly or configuration when the precise customer requirement is known. This type of postponement strategy moving the customer order point up-streams is utilized in the mass-customization industry separating “base” and “surge” demands. However, unlike the construction industry, the product design is often developed in a separate product development process in the manufacturing industry by the lead firm or system integrator.

Construction concepts and projects show different preparations before the customer order arrives and before realisation of the project. Figure 1 shows four different kinds of product specification processes before the customer order arrives, where the customer order decupling point are represented with a line dividing the product development of the building system from the specification process in the specific project, (Hvam et al, 2008). The dividing line represents how up-streams the customer enter in the product development process.

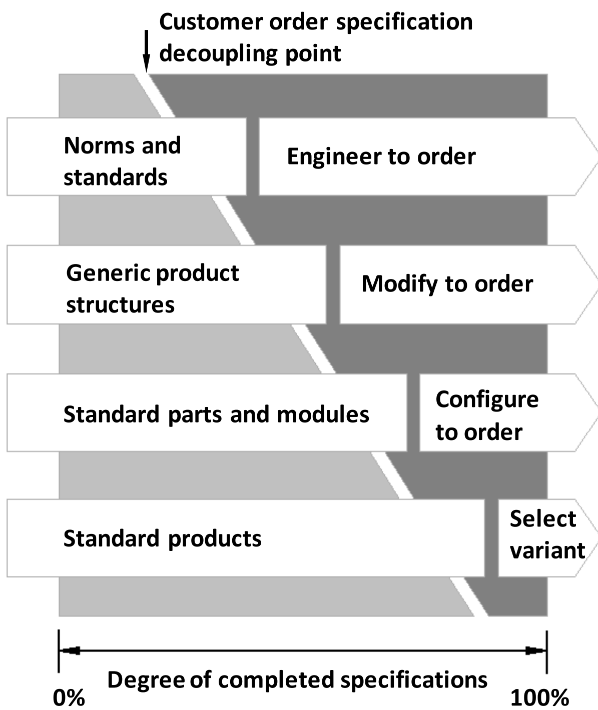

Figure 1: Product specification process for different variants of building system

2.3 Configuration

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

2.4 BIM tools for configuration

The CAD tools used in the construction today uses object oriented modeling such as; Revit™, ArchiCAD™, etc. that are derived from the object oriented parametric tools used in the mechanical industry. These CAD tools are commonly known as Building Information Modelling (BIM) software, (Eastman et al. 2008). According to Sacks et al. (2003), 3-D modeling software must support a top-down design process with three distinct phases: assembly layout, assembly detail, and piece detailing, whereas conventional construction object-based applications primarily focus lies on assembly layout with predefined “base building objects” (Eastman et al. 2008). In the work with integrated model-based design, Kunz and Fischer (2009) define three levels of virtual design and construction (VDC). First level *"Visual 3D and 4D models"*, second level *"Building Information Models"* and the third level named *"Knowledge-based models that support automation"* that uses parametric models to automate routine work, such as piece detailing. The idea of parametric modeling is that shape instances and other properties can be defined and controlled according to a hierarchy of parameters at the assembly and sub-assembly levels, as well as at an individual object level, (Eastman et al., 2008). When CAD application tools such as Revit™ are developed to assist the conventional construction process, these parametric support systems are developed to certify that all kind of technical solutions can be incorporated; "base building objects" (Eastman et al. 2008).

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

Johnsson et al. (2006) advocates the use of specialized software to solve problems they are designed for. Manufacturing industry has been working with rule-based programs since 1984 (Sandberg 2007) and has developed "expert systems" known as KBE, built on logic expressions and Boolean operators, (Hvam et al. 2008). The developed KBE system focus on design automation using object-oriented programming, configuration and engineering knowledge, (Sandberg, 2007). Sandberg et al. (2008) are, for example, using a rule based parametric CAD application normally used in the manufacturing industry in design automation of the connection between the stair and a wooden slab. One CAD-application used in the construction industry, ArchiCAD™, can with the use of a description language, GDL (Geometry Description Language), support programming of objects with constraints and design rules in the architectural design.

3 BUILDING SYSTEMS AND CUSTOMER ORDER DECOUPLING POINT

The first and lowest degree of a defined building system is the *Engineer-to-order* where the AEC industry design products in ordinary construction projects such as dwellings, offices, arenas and plants/factories. The design specification process is mainly based on client requirements, norms and standards.

So called technical platforms have recently been introduced in Sweden that fall in the category *Modify-to-order*. Typically, these systems have a generic product structure and constraints in measures and type of technical solutions to be used, such as standardized floor heights, a selection of approved technical solution of outer and inner walls and window types etc. The "NCC Bostadsplattform", is an example of this kind of building system on the Swedish market, see Figure 2.

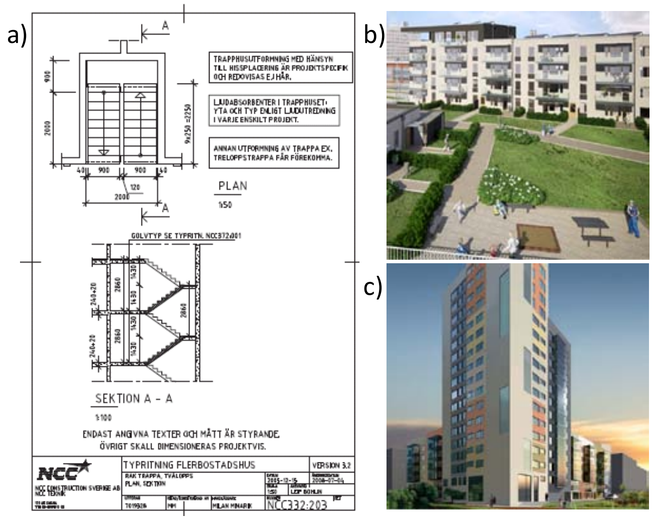

Figure 2: NCC building system "NCC Bostadsplattform" is of type generic product structure where a) show type drawing of the standard stair-case, b) and c) are on-going housing project where b) is designed according to version 3.1 and c) according to version 3.3 of the building system.

The *Configure-to-order* type of product offers are based on modules and standard parts that can be configured to satisfy customer needs. These type of building systems are relative uncommon. The “NCC Komplett” is an example of a more flexible and configurable building system that recently was closed down due high development cost and poor return on investment, (Andersson et al, 2010). The system consisted of configurable modules with all equipment, fittings, wallpaper and flooring attached to the elements before assembly on-site. Tyréns is currently developing an open "configure to order" type of building system that is based on configurable modules, see Figure 3.

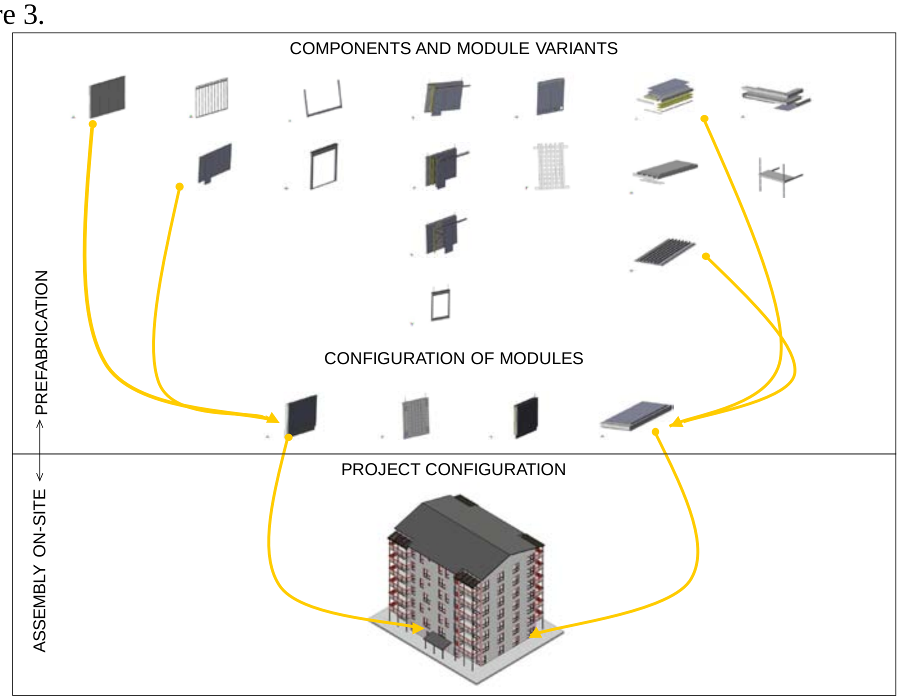

Figure 3: Tyréns wooden building system based on prefabricated configurable modules that are produced in factory and assembled on-site.

There are also a number of companies working with standard products in the construction industry, especially in the detached single house market where the customer *Select-variant* from a product portfolio or "product concept" often with only minor possibilities of customization. The building system, "Skanska ModernaHus", is an example of a select-variant building system that are currently being developed to offer more configurations for the customer. Today it consist of 3 - 8 storey apartment buildings with a number of floor configurations and add-on options including energy performance and exterior design, see Figure 4.

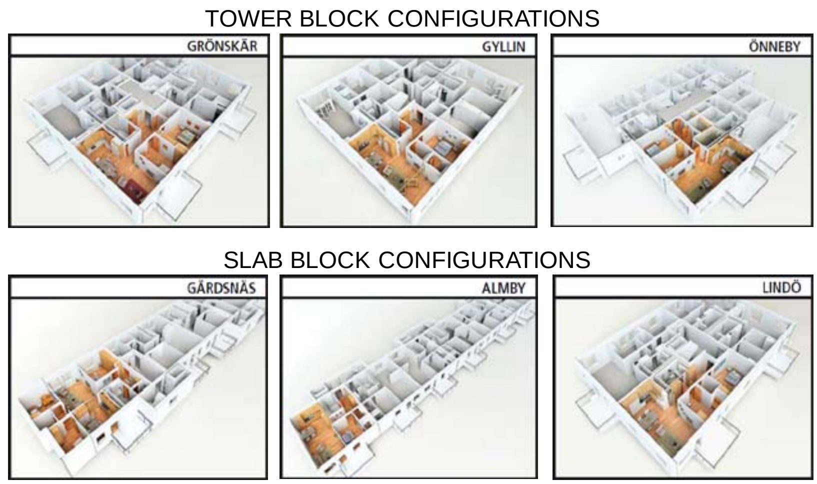

Figure 4: Skanska ModernaHus Select variant type of building system

4 PRODUCT VIEWS, FLOW OF INFORMATION AND CONSTRAINTS

Malmgren et. al. (2010) defined four product views relevant for industrialized building systems; customer, engineering, production and site assembly view. These views shows the product breakdown from the different stakeholders' perspective:

- The *customer view* contains the clients functional requirements and is created by the architect or sales department
- The *engineering view* is transformed from the customer view and detailed into building parts to be manufactured.
- The *production view* contains the necessary information needed to pre-manufacture the building parts
- The *assembly view* contains information on how to assemble the pre-manufactured building parts at the building site

Figure 5 shows the flow of information and constraints between the different views.

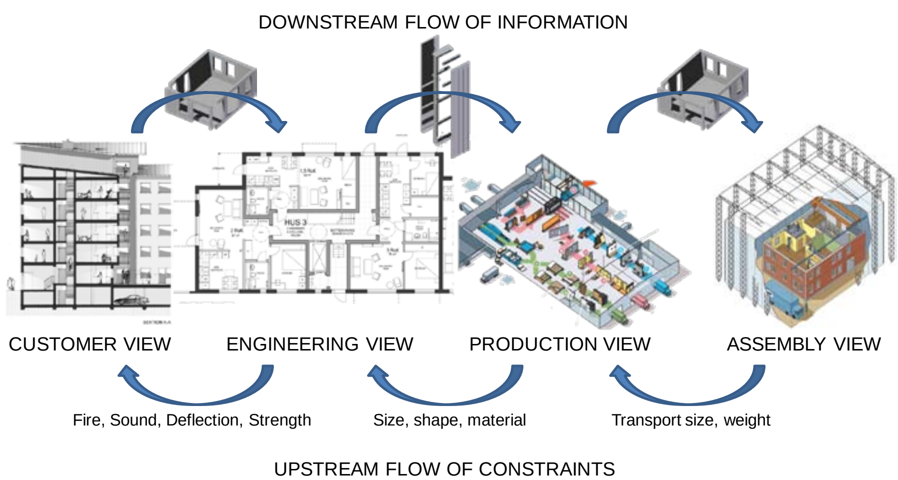

Figure 5: Downstream and upstream flow of information and constraints.

The downstream and upstream flow of information and constraints are highly dependent of the category of building system. In the case of engineered-to-order, e.g. traditional construction design, almost no formalized constraints from production and engineering flow upstream to the architectural design. On the other hand the select-variant need very little information from customer and engineering view since the possibilities for customization are small. The constraints are already built-in in the product, it's just a matter for the customer to select a pre-defined variant or look for another product.

5 CONFIGURATION STRATEGIES

There are primarily two different types of configurators: sales configurators and engineering configurators. Sale configurators are usually developed when the decoupling point is close to a completed specification, i.e. ranging from select-variant to configure-to-order. Engineering configurators are developed when products are highly configurable, configure to order - modify to order. When the solution space becomes larger traditional engineering methods are used.

5.1 Sales configurators

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

Figure 6 shows an example of a simple sales configurator for Skanska ModernaHus. The configurator can either be operated by the sales personal or put in the hands of the customer via a Web-based interface, Gilmore and Pine (1999).

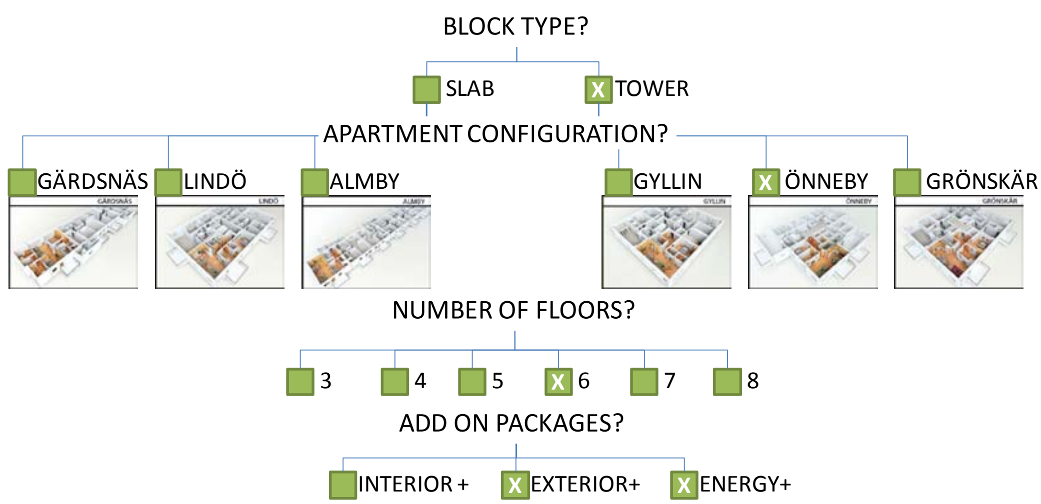

Figure 6: Example of a simple sales configurator for Skanska ModernaHus

5.2 Engineering configurators

Engineering configurators aims at speeding up engineering design by reusing earlier results and knowledge. With the use of expert systems it is possible to automate time consuming engineering activities, relocating time into improving old solutions or finding new ones, (Hvam et al. 2008). Another motivation for developing engineering configurators is to establish a firm link between sales and production encapsulating the flow of information and constraints downstream and upstream.

Jensen (2010) developed an engineering configurator demonstrator of the floor slab module in Tyréns wooden building system based on requirements in Table 1.

Table 1: Requirements from customer and production view on the engineering configurator tool

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

The engineering configuration demonstrator, see Figure 7, was implemented in Solid Works^{TM} using the add-on Tacton Works Configurator.

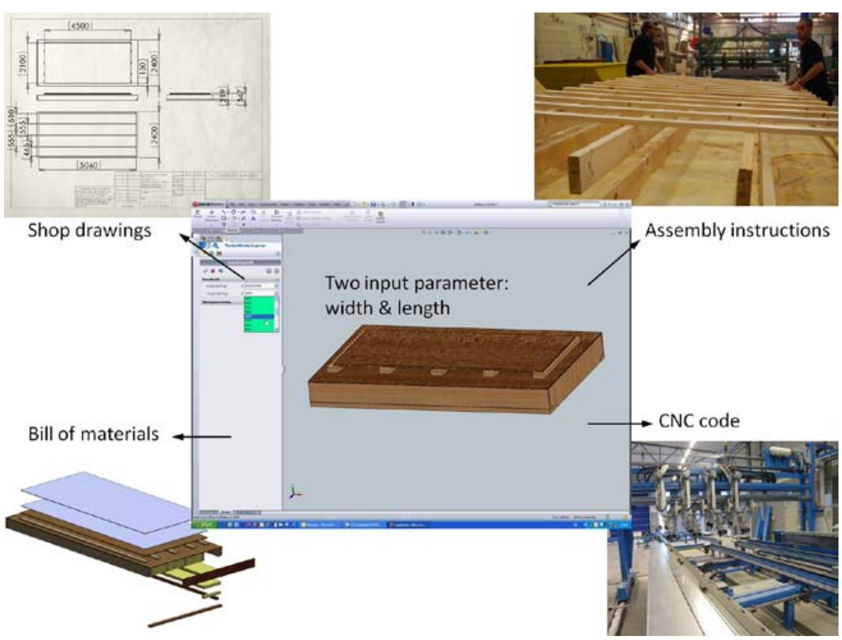

Figure 7: The implemented floor slab configuration demonstrator, Jensen (2010)

The detailing of the slab module needs two parameters the width and length of the slab. This can be accomplished either by the engineer or the architect partitioning the floor into appropriate slab modules. In the development project the building system modules was defined in the architectural tool Revit, as a family in the customer view. The floor slab family consisted of four different widths “600, 1200, 1800, 2400”, where the length parameter is parametric within the module limits and set with Revit accuracy scale “Course, medium, fine” using a grid of 150 mm. A distance parameter between modules was defined representing the interface when connecting the floor slab to walls in a kind of LEGO approach. The downstream flow from customer to the engineering view was demonstrated using XML export/import mechanism but could have been realized using IFC. However, a configuration control application that can analyze and map modules within the space boundaries given by the architectural design might be a better approach to get acceptance from architects.

6 DISCUSSION AND CONCLUSION

Building systems can be categorized according to the customer order decoupling point in the product specification process. The select-a-variant and configure-to-order type of building systems affect the traditional business process the most since it challenge the traditional way of doing design in construction. The type of building system a company determines to develop is a balance between flexibility of adapting to customer requirements and efficiency in design and production. Sale configurators are suitable to implement when the decoupling point is close to a completed specification, i.e. ranging from select-variant to configure-to-order type of building system. Engineering configurators are developed when products are highly configurable, i.e. configure to order - modify to order type of building system. When the solution space becomes larger traditional engineering methods are used.

Clear defined product views enables the integrating of flow of information downstream and upstream flow of constraints compared to the traditional way of working in the construction industry. However, this restricts the solution space but also opens possibilities for design automation. Rules and constraints can be concealed and information transfer kept small since much of the information needed can be transformed into formal computer interpretable knowledge that can be shared by the actors in the value chain.

In the customer view, the tools normally used by architect can be adapted, e.g. developing module objects or model checkers that obey rules and constraints imposed by the building system. Design automation in the engineering view, can be easily implemented in parametric tools and product configurators normally used by the mechanical industry. Selecting proper tools for the different views, reducing the information transfer using parametric and rule based solutions will minimize the risk for ad-hoc design solution propagating downstream to production and assembly on-site. This will also speed-up the design process and enable production to be automated. The paper demonstrates strategies for how information and constraints can be managed and transferred upstream and downstream using view specific ICT-tools. We believe that the use of these systems will also affect the engineers way of working and probably introduce new roles, e.g. configuration controller.

7 ACKNOWLEDGMENTS

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