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

Johnsson H, Jansson G and Jensen P (2013) Modularization in a housing platform for mass customization *In:* Smith, S.D and Ahiaga-Dagbui, D.D (Eds) *Procs 29th Annual ARCOM Conference,* 2-4 September 2013, Reading, UK, Association of Researchers in Construction Management, 91-100.

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.

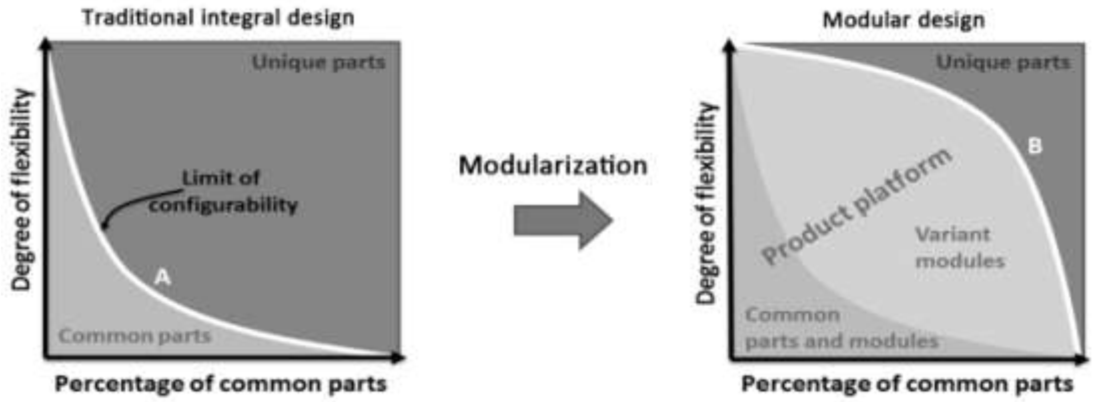

Figure 1. From integral to modular product architecture (Jensen et al. 2013)

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.

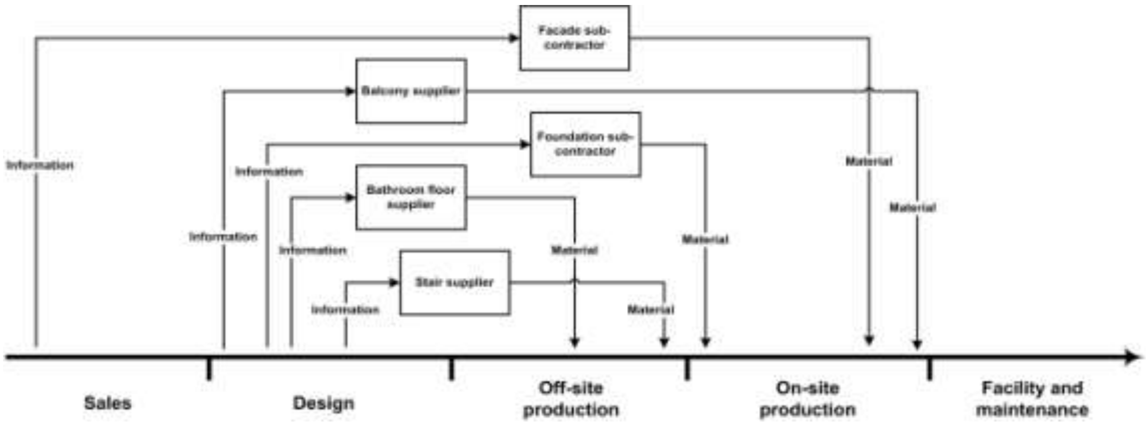

Figure 2. Parallel supplier and sub-contractor processes for the five studied sub-systems following the building process at the case company.

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 has 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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