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REDUCING COMPLEXITY OF CUSTOMIZED PREFABRICATED BUILDINGS THROUGH MODULARIZATION AND IT SUPPORT

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ABSTRACT

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

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

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

KEYWORDS

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

1. **INTRODUCTION**

Many of the Swedish prefabrication single-housing industries were established in the mid 60's. Prefabricated houses now dominate the single-house market in Sweden with a market share of as much as 80%. In the 60's and 70's the customer demands were low and architectural designs and technical solutions were standardized (Höök 2005*).* In the beginning of the 80´s competition in the single-housed market inclined and companies were facing new rivalry due to increasing demands on customized solutions, (Hill 1994). Initially well designed standardized technical solutions were transformed using *"ad-hoc"* solutions necessary to customize the house according to customers needs. This was, according to Brege (2008), one of the main reasons to the fall in profits in the prefabricated single-housing industries in the 80's.
Josephson and Saukkoriipi (2005) states that as much as 35% of the total production costs can be identified as waste in traditional on-site production of apartment blocks. This has inspired several constructions companies in Sweden to implement building systems for the production of apartment buildings. However, the question arises how the building system can be customized in order to be competitive on the market? Adaptation to the increasing demands for customisation is facing many industrial sectors around the world and, according to Ulrich and Eppinger (2008), mass customization methods can be used were the customer can tailor the product according to his/her own needs. Modular Function Deployment (Erixon 1998), is one strategy that can be adapted to prepare a product family for mass customization. One big difference when referring to methods used in the manufacturing industry is that they are developed for product oriented processes where a decentralized product development process are common (Johnson et. al 2006). The building industries are conventionally project-oriented, and methods that are used in the manufacturing industry must be adapted to the building industries way of working. According to Lessing (2006), the focus on the individual project in the building industry has often led to a fragmentation in the process with little continuity and low productivity development. Also, no single actor owns the whole process as opposed to the manufacturing industry, Nordstrand (2003).
The purpose of this paper is to explore methodologies for customization used in the manufacturing industry that in a structured way can evaluate customers demand against the possibility of customization of a standardized building platform.

2. THEORY

2.1 MODULARIZATION

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

2.2 MFD – A METHOD FOR MODULARIZATION

Modular Function Deployment or MFD is a method that systematically divides products or families of products into modules, based on five key steps. In step 1 the customer needs are recognized by using the Quality Function Deployment (QFD) method, (Akao 1990). After the product properties are determined from the QFD analysis, technical solutions that meet these needs are developed in step 2. When technical solutions are chosen, a module grouping process is performed in step 3 creating a Module Indication Matrix (MIM). This step identify *"module drivers"* that arrange the technical solutions into similar characteristics. The new concepts and the technical solutions are evaluated using an evaluation chart, step 4, where the identification and evaluation of module interfaces will be an important factor for which concept to select. When the modules are found they can be improved developing module variants with the same interface without affecting other parts (modules) of the product. Step 5, the design process or development of modules/ module variants can then be structured with methods like Design for Manufacturing/ Assembly (DFMA), (Erixon 1998)

2.3 QFD - TRANSLATING CUSTOMERS NEEDS INTO PRODUCTS

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

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

2.4 PRODUCT CONFIGURATION AND PRODUCT MODELS

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

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

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

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

3. THE PRODUCT CENTRIC BUILDING PROCESS

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

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

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

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

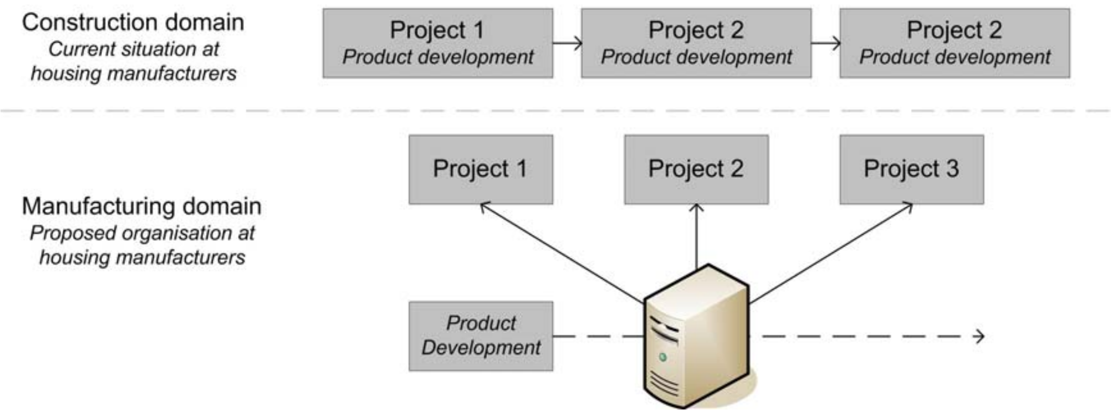


Figure 1: Project and product focused processes. (Johnson et al. 2006).

4. CASE STUDY- SMALL PREFABRICATING COMPANY

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

4.1 THE COMPANY IN THE CASE STUDY

The company involved in the case study is working with design and constructing of new small houses for family use. According to the owner, *"customers wish to buy a well design/ architect drawn house filled with dreams"*. Their new approach to the market is that they are delivering new designed houses in what they call a collection, 3-5 new types of houses every second year. They deliver complete material and components needed above the foundation including assembling instructions. The assembly of the house is left to be done by the customer. The material is delivered pre-cut together with components, such at fittings kitchen utilities, in a container and with little or no prefabrication what so ever. To sustain competitive advantages, the company needs to modularize the technical solution to find carryover solutions between collections.

4.2 TRANSLATING NEEDS TO PRODUCT PROPERTIES

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

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

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

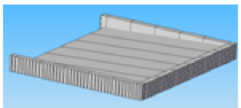
The target group in the case study can be said to be the design aware customer who want to own a unique architectural designed building. However, the price matters. From the market analysis, the proposed solution was to engage a known architect to do the design and as a compromise between uniqueness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

In this paper we will use the roof design proposed by the architect as an example, of how we can translate the functional requirements to roof properties. The requirements are listed on the left side and product properties on top of the OFD diagram in Figure 2.
The requirements part has been divided into 4 categories that will affect the technical design:

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

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

FLAT ROOF



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

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

4.3 RESULTS FROM THE QFD-ANALYSIS

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

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

4.4 MODULARIZATION PROCESS

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

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

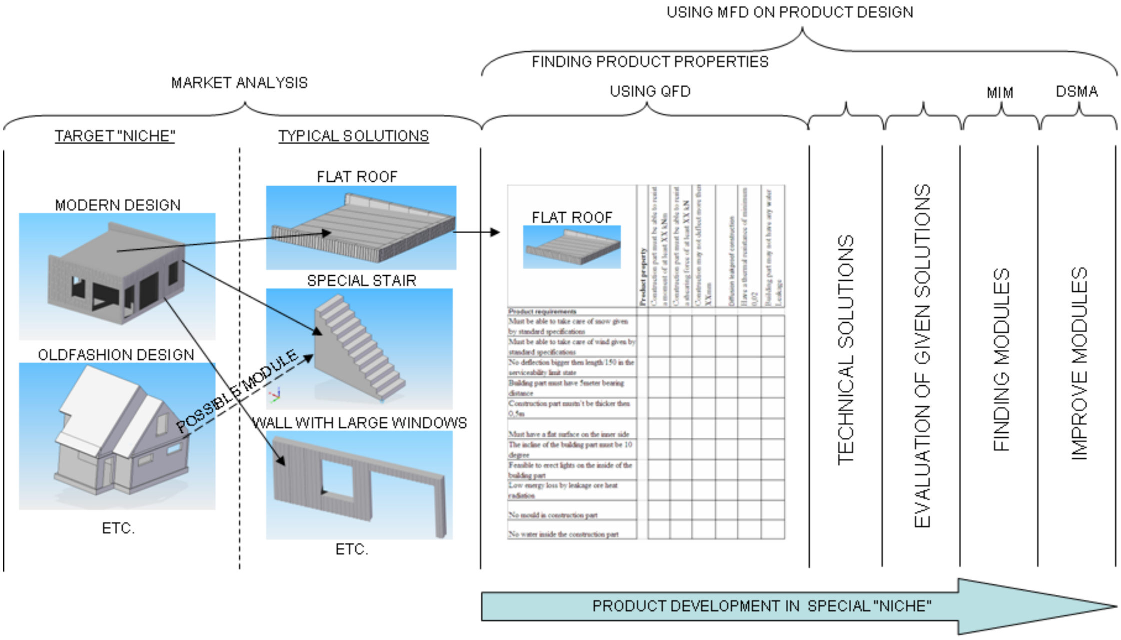


Figure 3: Product development of houses using modularization techniques.

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

5. DISCUSSION

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

Some manufacturing companies have attacked these problems and being successful using modularization to adapt their product and production system for mass customization. Why can't construction industries work in similar ways? Much of this problem dissolves from the fact that manufacturing industries are product oriented whereas construction is project driven. Contractual forms and number of participants often working in separated phases over the project life has separated design from production. Ad hoc solution to please a specific customer are causing problem in the production phase. According to Erixon (1998); "*the design phase can determine 75% of the production costs*". This has led to methods like MFD to put more emphasis on "Design For Manufacture". The problem of not specifying the functional requirements also from a production perspective leads to designs not really adapted for the production system. Methods like QFD can help to identify design properties that are vital both from a customer perspective and from a production system point of view. Methods like MFD can then be used to identify both process and product "modules" that can be re-used over time from project to project. However, it seems essential that the same actor in the building project is also the owner of the product. The most likely candidate is the building constructor making him the process owner. Then the benefits (but also the risk) of investing in new building system can be calculated over a time span longer than the individual project. Today, you often hear things like "this building is so unique and will only be built once" but many of the parts in the "unique" building are used over and over again in many construction projects.

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

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

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

6. CONCLUSION AND FUTURE WORK

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

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

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

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