USE OF MODULARIZATION IN DESIGN AS A STRATEGY TO REDUCE COMPONENT VARIETY IN ONE-OFF PROJECTS

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ABSTRACT

Standardization of work as an essential principle of lean management aims to improve the production process in construction. This paper describes a design strategy which aims to reduce the variety of building components, where this variety affects productivity negatively. The design strategy is based on modularization and standardization. We first review the roots of modularization and standardization, and distinguish the two concepts from each other. Then, we describe the design strategy, which is based on structuring of a building model and defining “modules”. The modeling strategy is implemented in two interrelated steps: (1) modularization, and (2) standardization. (1) The process of modularization defines 'chunks' in the building’s model and the interfaces between them. (2) The process of standardization aligns the structure of the modules to reduce the variety of components. Creation of these standardized modules during design improves application of standardized work and pre-fabrication. We present the described design strategy in two case studies: The first case study presents an example of implementing the design methodology, and the second case study describes the results of the design methodology in reducing the variety of the components. We conclude that modularization improves the potential for standardization in one-off projects, but it should be applied (1) early in design and (2) in an integrated team to identify customer value trade-offs.

KEYWORDS

Product variety, Modular design, Modular construction, Standardization, One-off projects.

INTRODUCTION

Construction projects can be characterized by three main peculiarities: site production, temporary production organization, and one–of-a kind product (Vrijhoef and Koskela

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2005). The focus of this paper is on the third peculiarity "one–of-a kind product". In comparison with other industries, construction projects are mostly one-off projects, where the repetitiveness of work is low, and construction projects can be seen as design-to-order production systems (Winch 2003).

Modular approaches to design and construction have gained popularity within the Architecture-Engineering-Construction (AEC) industry. Modular construction is associated with cost and time savings through prefabrication and off-site work. Modular design is mostly associated with the use of product platforms, which enable mass customization across several projects. However, pre-existing kits sets of building parts which are then kitted into individual buildings constrain design and may not always fulfil customer desire.

Thus, there seems to be a lack of methodology for modular design one-off projects, which do not draw from pre-existing product platforms.

The goal of this paper is to describe a methodology for modular design of one-off projects. This design methodology comprises the concepts of modularization and standardization. First, we present a literature review about the roots of modularization and standardization. Second, we describe the research question and the research approach. Third, we present the observed design methodology. Fourth, we introduce two case studies. The first case study presents an application of the design methodology. The second case study compares the complexity of the Mechanical - Electrical - Plumbing (MEP) systems design before and after application of the design methodology. Fifth, we present conclusions.

LITERATURE REVIEW

BUILDING COMPLEXITY AND ELEMENT VARIETY

Construction projects are frequently characterized as unique projects. This property adds complexity to the design and construction processes. Baccarini (1996) defines project complexity in two terms: differentiation of project elements, and interdependency between project elements. Differentiation refers to the number of different elements, e.g. tasks, specialists, or components, while interdependency looks at the relationships between the elements (Baccarini 1996). Weber (2005) describes five sources of complexity, and one of these is variational complexity: it refers to the number of different component or system variants. Hobday (1998) states that component or system variety causes uncertainty in design and construction. Tommelein (2006) shows that the variety of components adds complexity to the construction process, because it can create variations in the work flow, which may affect productivity negatively.

ROOTS OF MODULARIZATION AND STANDARDIZATION

Although the term modularization is often used in literature, there is no consensus on the definition of this concept and the proper use of it (Gershenson et al. 2004). Modularization deals with the configuration of a product from modules, which can be seen as chunks of the product. Standardization means using identical components or sub-systems across products (Fixson 2007) or within one product. The degree of modularity in a product's architecture depends on several issues, such as, product change, product variety, and component standardization (Ulrich and Eppinger 2004).

Next, we present the concepts of modularization and standardization in some early references to research the origins of these concepts. Table 1 shows detailed information.

Alexander (1971) introduced the idea of diagrams or patterns as a key concept for creating the form of the building. Although Alexander did not use the term modularity, this concept is obvious in his ideas about design. Alexander defines the design problem by a set of requirements and interactions between them. He addresses the decomposition process of requirements into subsets as a challenge during design. The task is to divide the requirements into subsets which are connected by a few links as possible as and leaving as many of the links as possible within the subsets. This establishes a hierarchy of subsets of requirements, and each subset can be solved independently of other subsets. Alexander emphasized that conflicts between requirements must be solved as early as possible in design.

In the field of software design, Maynard (1972) addresses that the first idea of modular design in IT was to improve the throughput of a programming department by writing programs as small manageable segments that can be scheduled and developed independently. Designers define modules by splitting program specifications into chunks; this process depends on the logical functions required by the program. Each module shall perform a single logical function or a number of small related logical functions. The goal is that each module can be developed and tested independently. Maynard (1972) defines standard modules as follows “A standard module performs function which is known to be required in future programs or which has a high possibility of that”.

According to Baldwin and Clark (2000) “Modularity is a design structure, in which parameters and tasks are interdependent within the modules and independent across them”. The process of modularization includes dividing the design parameters into design rules and modules' parameters. Baldwin and Clark (2000) address two issues for the concept of modularity: (1) interdependence within and independence across modules, and (2) abstraction, information hiding, and interfaces. The design hierarchy indicates which information is hidden or visible at different levels of the hierarchy. Visible information is called design rules and is inputs to all subsequent levels; it affects the modules’ design. Change of the design rules affects the design of all levels of the hierarchy, where this information is visible. Therefore it is important to define and set the design rules early in the design process. According to Baldwin and Clark (2000), as it is addressed by Alexander (1971), points of interaction between modules shall be as few as possible.

Wiendahl et al. (2005) present a concept of modularization for factory buildings. Modularization is considered a core concept to make either individual production systems or the whole factory flexible, and thus robust against future changes in requirements. The requirements of flexibility of a factory building and their effects on the production system must be determined. Wiendahl et al. (2005) define five planning fields and three configuration sectors for the design process. Each module must be assigned to one planning field and one configuration sector. The concept allows for a hierarchical structure by defining sub-modules. During the design process, standard elements shall be used to create modules, and the modules may be reused in the five different planning fields of the factory, thus fostering standardization of modules.

To summarize the presented literature:

- It is important to begin modularization early in the design process. A hierarchical structure of systems is the core concept to start with and to apply modular design.
- Setting interface values between modules early in design and hiding of information reduce flexibility during the design process. This may hinder innovation and thus reduce product performance, compared to a product without a modular structure (Ulrich and Eppinger 2004).
- Standardization can be seen as a part of modularization and standardization can be applied to elements inside each module, to the interfaces between the modules, or to modules. Standardization can be applied within one product or across different products.

MODULARIZATION AND STANDARDIZATION IN THE AEC INDUSTRY

Literature shows different uses of the term ‘modularization’ in the construction industry.

Court (2009) defines modularity in production as an assembly system where modules consist of components that can be combined off-site and then delivered to the construction site. CII (2011) identifies potential improvements, such as lower cost, shorter schedule and better quality, through the use of pre-designed modules across several construction projects. Standardized modules can be combined to produce a customized product. Thus, the design phase becomes a configuration phase, in which designers combine available modules into a customized product (Jensen et al. 2009). Veenstra et al. (2006) introduce a platform-based methodology emphasizing the importance to balance standardization and variation in order to meet the different customer values. Lennartsson et al. (2008) emphasize the importance to balance customer value and delivery team value when defining product platforms and modules in industrial housing.

The presented approaches apply modular design by using standardized modules across several projects. This paper discusses a design methodology for modular design of one-off projects.

RESEARCH QUESTION

Our research question is: How can we improve the potential for standardization of building components and construction operations during the design phase of one-off projects, which are not to be kitted from pre-existing sets of modules?

Table 1: Literature review on origins of modular design

Reference	Goals	Module definition	Interface definition	Methodology of modularization	Customer value
(Alexander 1971)	Create a single whole form from patterns or „diagrams”, which can be studied and improved one at a time. Create an infinite variety of designs by various combinations of standardized patterns.	“A diagram is an abstract pattern of physical relationships which resolve a small system of interacting and conflicting forces, and is independent of all other forces, and of all other diagrams.”	“The interaction among the requirements spring from the intractable nature of the available materials and the conditions under which has to be made.”	Define diagrams in a way that the requirements in the different diagrams are as minimally as possible constraint by requirements from other diagrams. Minimize information transfer or informational dependence called $R(\pi)$.	Enabling design of complex projects through independent design-problems.
(Maynard 1972)	Improve the program quality, department flexibility, schedule, productivity. Using of standardized modules within the same program and across the programs.	Modules are small sections of easily reusable code. The modules can be called to perform certain functions.	An interface is the communication between modules.	Modularization through splitting of program specification; logical functions required from the program determine the modular structure.	Reduce time and cost for development and maintenance through parallelization of work packages.
(Baldwin and Clark 2000)	1. Manage complexity. 2. Parallel design. 3. Reduce uncertainty. 4. Using of standardized modules across a product or product family.	“[A] module is a unit whose structural elements are powerfully connected among themselves and relatively weakly connected to elements in other units”.	“The interfaces are detailed description of how the different modules will interact, that is how they fit together, connect communicate, and so forth” interfaces are visible information.	“Modularization involves: 1. Promulgating of design rules, and 2. Severing connection between task blocks, where detailed knowledge will be needed about the interdependencies.”	Economies of scale and faster innovation cycles through re-design of modules instead of whole product.
(Wiendahl et al. 2005)	Reduce complexity of the factory and make it robust towards future requirements. Use of standardized modules to increase productivity in design.	A module is a set of elements; it represents a limited technical, organizational or spatial range, and it is reusable and isolated from the other modules.	Interfaces between modules are: 1. Element-relevant interfaces, e.g., information, communication, material, personnel. 2. Non-element relevant interfaces. e.g. climate, noise.	Development of the modules depends on the flexibility and the properties of the module’s components (or sub-modules). Modular design consists of four phases: (1) Separation (2) Structuring, (3) Configuration and (4) Implementation.	Sustainability of factory buildings through flexibility for future requirements. Reduced cost through re-use of modules.

RESEARCH METHOD

One of the authors of this paper was involved during the design phase of the two case studies presented here. He co-developed the presented approach for standardization and modularization of one-off projects. Thus, the two case studies were conducted as action research. The results are grounded in an extensive literature review on modularization and standardization in several disciplines.

METHODOLOGY FOR MODULAR DESIGN OF ONE-OFF PROJECTS

This section presents a methodology for modular design of one-off project. The main idea of this methodology is that every building consists of similar spaces, either through geometry, use of the spaces, or structures. Identification of these similarities enables standardization of the building parts, which in turn helps in improving construction processes.

The methodology consists of two interrelated processes:

- Modularization aims to structure the building or parts of it into chunks, called modules, which sparsely interact. Structuring defines interfaces between modules.
- Standardization aims to group similar modules in one type of module, and tries to minimize the different types of modules. Minimization of types can include changes to the design of modules.

Both processes are applied on 3 levels: (1) building geometry, (2) space utilization, and (3) building components. Both processes are interrelated and designers iterate between them to minimize the types of modules in every level. When designers identify new design requirements in the later phases that demand changes of modules, they may iterate between levels. In order to identify requirements, application of this methodology needs customer involvement.

In the following section we present two case studies. The first case study presents an application of the design methodology. The second case study compares the complexity of MEP Systems before and after imposing the methodology on the existing building design.

CASE STUDIES

CASE STUDY 1

The first case study presents the design process of an office building of 24 floors and 45,000 m², which was built between 2000 and 2002. The above presented design process was implemented, beginning in the detailed design phase.

Building Geometry

Modularization started by defining a grid system for the building. The size of grid units is standardized, and it is determined through the area in the geometry that allows for the maximum number of identical spaces in the building. Figure 1, left hand side, shows the grid system in green below the building. Positions of typical elements of the building geometry, such as columns, facade elements, or shear walls, help during grid definition. The goal is either to completely put an element into one a field of the grid, so that the interfaces of the element align with the gridlines (e.g., facade elements), or to put the element on the gridline, so the element becomes part of the interface (e.g. columns). Standardization starts with grouping similar fields into 'types', e.g., the grid fields located in the corners of the building are similar, because they have outside walls on two sides, and thus, constitute a type of field. Next, designers align the structure of fields of the same type by making small changes in the building design, e.g., moving a column onto the gridline between two fields. In order to minimize the number of types, it may be necessary to change the earlier defined grid system. The customers must be involved in this process in order to weigh the value of standardization against the impact of changes to the design quality of the building.

Space Utilization

Modularization begins with assigning a category of space utilization to each field. The goal is to align boundaries of spaces that have different utilizations with the interfaces between fields of the grid. Figure 1, left hand side, shows the different utilizations of building space in shades of grey. During standardization, the goal is to minimize the number of categories and also to maximize the alignment between the types of grid fields and the categories, e.g., all corner fields of the building shall fall into the same category of space utilization. This process can include changes to the categories of space utilization, and also changes to utilization of spaces. The customer must be involved in order to weigh the value of standardization against the impact of changes in the utilization of building spaces.

Building Components

Modularization begins by assigning systems' components to fields of the grid. The goal is to align boundaries of systems with boundaries of fields of the grid. For example, changes in the diameter of ducts lay on the interface between two fields, so that each field contains minimum number of different types of duct. Figure 1, right hand side, shows the structure of building components in the grid and the different types of spaces including different configurations of components. During standardization the goal is to minimize the number of different configuration types for each type of field and also across different types of fields. Using a larger duct diameter than necessary in some parts of the building enabled a greater standardization of components. The customer must be involved in order to weigh the benefits of standardization, such as easier construction operations, against a higher cost for material.

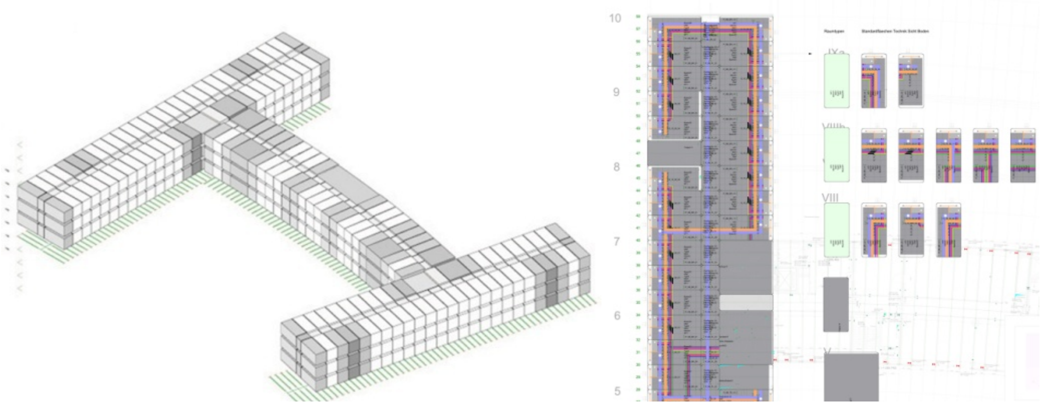

Figure 1: Structure of building geometry and space utilization (left hand side); structure of building components (right hand side).

Results of Application of the Methodology

Application of modular design reduced building complexity greatly. The design methodology triggered beneficial discussions between designers about trade-offs between standardization and variation, which improved the building design in accordance with customer value. Also, the new design enabled the use of a different installation process of the heating system. Originally, it was planned to wield hot-water pipes in place, but standardization of structures enabled off-site pre-fabrication of pipe systems. This new production process was expected to reduce 25% of cost and 60% of scheduled time. Unfortunately, these savings in the cost and time could not be realized. The now faster installation process could not be executed in a continuous flow, but instead in a stop-and go manner, because it's speed was not aligned with the speed of the other installation processes. Figure 2 shows, left hand side, the pre-fabricated materials pipes, and right hand side, the final product in place.

Figure 2: pre-packaged materials for MEP-system installation (left hand side); installed MEP systems (right hand side).

CASE STUDY 2

In this case study, we present the results of applying the design methodology on an existing building design. Comparison of original design and modular design shows the potential benefits of the methodology. Subject of the comparison is a sector of the building of 1000 m² (Digitales Bauen 2008). It must be noted that this comparison is theoretical, because the modular design was not built. Nevertheless, the comparison shows that the methodology reduced variety of MEP systems' components and structures.

Ventilation System

Comparison between original (before) and new (after) design is based on three criteria: (1) number of leaps in height of ductwork (before 21, after 0), (2) number of changes in ducts' dimension (before 27, after 14), and (3) number of different components of the ventilation system (before 48, after 14).

Connection Components of Ventilation, Exhaust, and Fire Protection Systems

The comparison criteria were: number of different outlets (before 43, after 36), number of outlets located on the interface between two modules (before 15, after 36), number of outlets not located on the interface between two modules (before 28, after 0), use cases of standardized structures (before 11, after 33), use cases of special structures (before 33, after 0), number of different structure variants (before 25, after 3), number of cases with good montage conditions for outlets (before 26, after 36), number of cases with easy installation conditions for outlets (before 17, after 0).

The reduction of the component variety is assumed to have little effect on customer value. Capacities of systems were not changed, while the changed 'look' of the MEP-systems is hidden in the suspended ceiling.

CONCLUSIONS

Product variety impacts process variation, and both case studies show that the presented methodology for modular design of one-off projects reduces the variety of components. Finding patterns in geometry during design improves standardization in the one-off projects, although, a practical case study will be needed to measure the effects on the construction site. Thus, the presented methodology has the potential to improve construction production processes. The methodology has the greatest impact when applied early in design.

In case study 1 not all benefits of standardization could be harvested. This case study shows the importance of integrating the customers and their values, including the contractors, into the design process through an integrated team approach. Further research is necessary on the application of the methodology in an integrated team, its decision making process, and the trade-offs between values of different customers. An integrated team approach can ensure that design improvements for a more efficient construction process can actually be harvested during construction. Also, a combined application of modular design and modular assembly (Court 2009) seems promising as it presents great potential for further improvements of the construction process. Further research is also necessary on cost and time savings, because these will influence customer value.

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