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A methodology for the optimal modularization of building design☆

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ABSTRACT

The use of prefabricated modules has the potential to increase the efficiency of onsite construction activities, as well as the adaptability of buildings. However, such modules currently require a degree of repetitiveness to which many clients object. To resolve this conflict, a graph-based methodology is proposed that decomposes the design into non-repetitive modules that can be preassembled offsite, without restricting the design in advance. Such modules contain components that have similar future replacement rates, and a limited number of connections to other components. A clustering algorithm is applied on data from BIM tools for an optimal definition of the modules and their interfaces. A computer program is developed to allow the automated application of the methodology in large and complex projects. The research demonstrates that graph-based models can be useful for representing and analyzing construction projects. A graph-based approach has the potential to be successfully applied in additional areas, in order to provide project management tools.

1. Introduction

Prefabrication of building components and modules has been promoted over the years as a way to improve value for money in projects. In prefabrication and preassembly, a substantial portion of production and final assembly work is carried out, often off-site, prior to the installation of components in their final position [1]. This approach adds value to projects by increasing predictability and efficiency, which in turn improves quality and minimizes the project duration [2].

The use of modules (i.e. prefabricated assemblies of components) can reduce the dependencies between construction activities that are carried out on site by different subcontractors. This, in turn, will increase the efficiency of the construction processes. Many of these dependencies are a result of physical interfaces between the components constructed in different activities. A delay in one such activity consequently has knock-on effects that cause additional delays in the other activities. The fact that interdependent activities are often carried out by different subcontractors increases this problem, as each subcontractor seeks to optimize the allocation of his resources among a number of projects he simultaneously carries out, and is less concerned with the effect that delays in his activities have on other subcontractors in the same project. Off-site production in construction offers the benefits of reducing congested work areas, and the interfaces between different trades [3]. This, in turn, can reduce disruptions of on-site activities [4].

One approach to reducing dependencies between onsite activities, which are due to physical connections between different components, is the use of buffers in project planning. However, buffers generally involve the allocation of additional resources, such as time and manpower, which carry a cost. The present research seeks to contribute to reducing this problem through the careful management of certain interfaces between components in the design, limiting the need for buffers. In defining the optimal modularization of the design, it focuses on the connections between components, rather than on the classification, according to the Product Breakdown Structure, of the building systems to which these components belong.

In addition to increasing the efficiency of initial construction processes, modular construction has the potential to increase the adaptability of a building throughout its life. Buildings are unique products because of their long life cycle, and the many changes they undergo throughout this lifecycle. Most buildings are constructed at a significant cost and are expected to be functional for many decades to come. In practice, most buildings are, however, designed to suit their use at the time of their construction, and their future adaptability is ignored [5]. As a consequence, components whose replacement occurs at different intervals throughout the extended life of the building are currently often physically and functionally connected to each other. The result of this is that minor changes require the demolition and replacement of many components, including those that otherwise would not have been replaced.

In the present research, the adaptability of buildings is increased by facilitating a systematic separation of building components with different replacement rates into distinct modules, which can be prefabricated offsite. These modules are linked to each other by a limited number of

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interfaces that can be easily disconnected. This can simplify the future renovation and adaptation of buildings to varying user needs.

1.1. Proposed approach for building design modularization

Despite the potential advantages of the use of prefabricated modules in construction, it is currently unpopular among many clients. An important reason for this is that a relatively high degree of *standardization* is often required, in order to achieve economies of scope and sufficiently reduce costs. Standardization is considered to include, in this context, the extensive use of components, methods or processes with regularity and repetition [1]. There appears to be an inherent conflict between standardization in construction projects on the one hand, and the satisfaction of individual client needs and desires on the other. Today's clients often demand maximum choice in the design of buildings, and there is consequently a need to resolve the conflict between the standardization and uniformity required to ensure that the prefabrication and preassembly of components are economically feasible, and the flexibility and variation that are required to satisfy client requirements [6].

An alternative approach that can resolve this conflict is the use of customized, non-repetitive assemblies of components with standardized interfaces, which are prefabricated offsite. Previous studies have noted the need to move from mass production to mass customization in off-site manufacture [7,8]. The standardization of certain interfaces between assemblies of components, rather than of the assemblies themselves, can ensure their accurate fit and interchangeability, without restricting the design in advance to a limited choice of repetitive units (Fig. 1). It can increase both the efficiency of construction processes and the adaptability of the building throughout its life. Such an approach thus simultaneously addresses both *process* and *product* modularity [9].

Process modularity aims at decoupling activities in time (by spreading activities over multiple time intervals) or place (by carrying out activities on dispersed locations). Product modularity, on the other hand, aims at decoupling the components in a product, in order to allow them to be easily changed or upgraded over time. As will be demonstrated, product modularity can facilitate process modularity, by reducing the interdependencies between construction activities that are carried out by different subcontractors. Thus, customer requirements for flexibility and variation in the project can be satisfied, while at the same time increasing quality and minimizing project duration.

The approach followed in this research is related to similar strategies employed in product architecture. Modular products can generally be divided into three typologies [10]:

- Slot modularity, in which the interfaces between the components are different, so that the components in the product cannot be interchanged with ease
- Sectional modularity, in which components are connected through identical interfaces
- Bus modularity, in which a single component (the bus) connects the components.

In this research, a sectional modularity is used. The standardization of the interfaces in between components ensures a loosely coupled design of the modular product [11]. By ensuring that the standardized interfaces between the components remain unchanged, a flexible product architecture is created, allowing a range of variations in components. Components can thus be substituted without having to change other components in the product [12]. Each component is treated as a “black box” by the product developing firm, which provides suppliers with the specification of only the interfaces of the required component, leaving the actual design of the component to the supplier. This strategy has been implemented, for example, in the car and software industries. Thus, Chrysler made a strategic shift in the 1990's towards a more modular product design, in which its suppliers–partners independently developed and built entire subsystems [11]. NASA has been using modular software systems for decades, in which loosely coupled modules are written independently, allowing them to be reassembled and replaced without affecting the design of the entire system [12].

Some examples for the use of non-repetitive modular components with standardized interfaces can already be found in the construction industry. This approach is enabled by new cost-effective automated technologies that include both design technologies such as BIM, as well as production technologies such as CNC cutting machines, 3D printers and assembly robots [13]. The second author has implemented this approach in building projects in Europe and Japan for the past three decades.

Examples for non-repetitive modular components can be found in façade systems of certain buildings, where individually shaped façade panels are attached to a structural frame. While they are connected through interfaces with a standard profile, these panels can have different forms, and contain different materials and components such as windows and ventilation grilles. In other projects, the ducts and pipes that are suspended from sections of a corridor ceiling have been preassembled offsite on steel frameworks, creating integrated electrical–mechanical system modules that are then attached to each other on site with standard fittings. An additional example is a Robotic Service Wall that was developed in a two year funded project called LISA — “Living Independently in South Tyrol Alto Adige” [14]. This wall contains different modules such as robotic actuators, sensors and display screens, in order to enable an Ambient Assisted Living approach. The proposed system can be arranged and re-arranged into various configurations, and can be easily installed in any residence without requiring specific space dimensions, through standardized interfaces with the other building systems (Fig. 2).

1.2. Current challenges and research objective

To summarize — the use of prefabricated modules in construction has the potential to increase the efficiency of onsite activities, as well

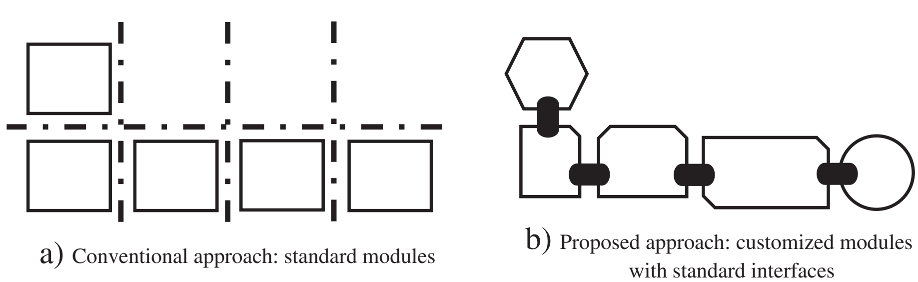

Fig. 1. Proposed approach for standardization of interfaces between modules.