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Automated spatial design of multi-story modular buildings using a unified matrix method

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ABSTRACT

Automated design methods facilitate the study of the influence of design forms on the buildings' behavior, and help compare the performance of alternative designs more effectively. This paper presents a Unified Matrix Method, as an effective automated method that aids in the search for the best compromised spatial design of multi-story modular buildings during the early stages of the design process. The method is presented in a general format employing a balanced approach that integrates different design aspects together, namely constructional, architectural and structural aspects. First, it describes how the spatial design of multi-story modular buildings can be generally represented by three-dimensional matrices arisen from combinatorial problems. Then, the spatial design is modeled by a design structure matrix, which decomposes the building into smaller components such as modular units, connections, stabilizing and bracing systems. Finally, a three-dimensional assignment problem is formulated to solve the problem. Particular conditions or preferences for the spatial design can be incorporated as constraints on the assignment problem. In order to show the robustness of the method, an actual case study is designed and employed, with the aim of obtaining a spatial design having minimum construction cost, maximum plan regularity and maximum energy efficient form.

1. Introduction

There is a growing demand for the construction industry to provide better value by delivering improved quality, higher performance and increased sustainability. The recent rise in Building Information Modeling (BIM) is providing exciting opportunities for the increased use of prefabrication and modularization in larger and more complex projects in the future. Accordingly, there is increasing reliance on modular buildings, as an alternative to conventional building practices, in a market pursuing faster and more sustainable construction. In fact, despite great technological progress in various aspects of building design and construction, the greatest potential for radical improvement of quality and productivity still remains with maximum prefabrication and modularization of building components.

Modular construction is a term used to describe the use of factory-produced pre-engineered large volumetric building units that are delivered to site and assembled as substantial elements of a building. The concept of modular construction is not new, but it is being greatly revitalized by recent technology advances that allow for constructing modular units of various characteristics, which in turn, provide a variety of building forms. The advantages of modularization increase considerably if the building has repeatable spaces. Examples of such repetitive units can be easily seen in a variety of mid to high rise buildings such as hotels, hospitals, schools, residential and commercial apartment buildings.

Design of buildings using modular construction is a complex inter-relationship between the desired space and the building's functionality together with the economical use of similar-sized modules. Despite some barriers and limitations placed upon designers such as lack of knowledge and specific standards and specifications, together with negative market perception based on built precedents, modular systems have been progressively adopted in the construction industry in various countries [1]. McGraw-Hill Construction [2] presented in a survey that the motivation for using modular construction generally arises because of the requirements for speed of construction, improved quality, better predictability, reduction in waste and consequently life cycle cost and embodied energy. Tam et al. [3] provided a feasibility analysis in the necessity of adopting prefabrication in construction activities, because of the considerable life cost saving that can be achieved through waste reduction.

Since 1990′s when load bearing modular units were first employed in multi-story buildings, a large number of mid-rise buildings have been constructed worldwide, using these systems. Recently some companies are using modular units in high-rise building construction [1,4].

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Lawson et al. [5] had a review of modular technologies to show how the basic cellular approach in modular construction may be applied to a wide range of building forms and heights. Chen et al. [6] presented a tool, designed to aid building team members during early project stages in evaluating the feasibility of prefabrication and exploring an optimal strategy to apply prefabrication in concrete buildings. Jaillon and Poon [7,8] reviewed the evolution of prefabricated systems in high-rise residential developments in Hong Kong. Baldwin et al. [9] described how modeling information flows in the design process and how it can be used to evaluate pre-fabricated design solutions when seeking to reduce construction waste in high-rise residential buildings. Nasereddin [10] et al. proposed an automated approach for developing discrete event simulation models for the modular housing industry. Alfares and Seireg [11] investigated the feasibility of automating the on-site construction of reinforced concrete residential buildings using modular forms. Retik and Warszawski [12] described a knowledge-based system for the detailed design of prefabricated buildings, which employs a comprehensive approach, and integrates different design aspects, architectural, structural and technological.

Early decision making can have the maximum influence on the final design and project cost. As much as 80% of the total resources required to construct a building are committed by the decisions made in the first 10% of the design process [13,14]. The majority of the economic and environmental impacts of buildings over their entire service life are also decided upon in the early design stages. Negative impacts from inappropriate building forms compound structural and constructional inefficiency and result not only in additional initial cost, but also in rising maintenance and operating expenses. In an integrated design procedure, where planning, design, construction and facility management are integrated into one system, selecting an appropriate spatial plan/form for a building is of great importance, as it influences all subsequent stages of the design process.

Automated early stage design of buildings has been an object of research in the recent decade. Sharafi et al. [15–17] developed some innovative design methods for automated conceptual design of frames, which considers cost factors in the early stage design. Granadeiro et al. [18,19] presented a methodology to assist design decisions regarding the building envelope shape considering its implications on energy performance. Delgado and Hofmeyer [20] developed automated computational processes that simulate a spatial structural design process to aid in the understanding of design processes and to support the involved participants. Yi and Malkawi [21] introduced a new method to control building forms by defining a hierarchical relationship between geometry points to allow the user to explore the building geometry without being restricted to a box or simple form. Yu et al. [22] used the design structure matrix (DSM) to visualize the architectural design and to develop the basic building blocks required for the identification of product modules.

In the recent decade, there has been considerable progress in the automated early stage design of conventional buildings. Several efficient methods have previously developed using graph products, which not only represents the connectivity in a compact form but can be employed in the analysis and design of conventional structures [23–26]. However, in most studies many structural and constructional constraints have not been adequately addressed. The absence of structural and constructional considerations in selecting an appropriate spatial design for buildings in the early stage design can seriously affect the final outcome. In practice, structural analyses and evaluation of many constructional issues are often performed at only the last stages of the design process. By considering structural and constructional matters at the early design stage, and allowing the designers to evaluate and analyze their own designs, a better integrated design could be achieved, and both structural and spatial requirements could possibly be better fulfilled.

In order to develop an effective early stage decision-making tool, designers must be enabled to understand how their decisions impact the structural and environmental performance, life cycle cost and how to address constructional matters of the building. This paper develops a novel matrix based methodology that enables designers to evaluate design options for modular buildings during the early stages of the design process, and compares the effect of forms on the performance of alternative designs. The methodology enables the designers to systematically model the structure of complex modular buildings to perform system analysis, project planning and design, and provides useful information on the design's behavior at the early stages of the design process. Since the methodology is presented in a general format, it can be employed to meet various objectives such as life cycle cost, structural behavior, structural stability, land usage, energy efficiency or any other objectives, depending on the problem in hand. By producing a design matrix that represents modular building of any forms, the methodology will significantly facilitate the automated generation of a thorough detailed spatial design model from the preliminary conceptual design as well [17,27]. This automated design technique can also assist the designers to compare costs, environmental impacts and structural performance of the design alternatives at the early decision making stages. The methodology will also give academic insight into the relationship between the elements of spatial planning and structural design and serves as a supporting tool for exploration of forms for decision making. The entire methodology has been programmed as a code in MATLAB at this stage of the research, and the visualization of the entire process in a toolbox is underway. In the existing version, the final outcome of this methodology will be a special design matrix that can be easily utilized as an input for the phase of detailed design, by employing a variety of existing matrix methods [26].

2. Modular systems for high rise building

Modular construction is used to create cellular-type buildings, which consist of similar room-sized units of a size suitable for transportation. These units can be manufactured in partially or fully open-sided forms, so two or more cellular units (modules) can create larger spaces. Modular units being used in practice are either supported on

Fig. 1. (a) Continuously-supported module; (b) corner-supported module.