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Decision support for construction method selection in concrete buildings: Prefabrication adoption and optimization

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ABSTRACT

Prefabrication offers a substantial opportunity to improve projects' sustainable performance. However, decisions to employ prefabrication are still largely based on familiarity and personal preferences rather than rigorous data. Methodical assessments of an appropriate construction method for a concrete project have been found deficient. This paper presents an objective and transparent tool, the Construction Method Selection Model (CMSM), which is 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. The model is divided into two sequential levels: the strategic level and the tactical level, respectively. The Simple Multi-Attribute Rating Technique (SMART) is used in the first level for preliminary feasibility evaluation of prefabrication. The Multi-Attribute Utility Theory (MAUT), which considers uncertainty and risk attitude, is employed in the second level to assess to what degree of prefabrication is appropriate for the project at hand. A detailed case study through in-depth personal interviews with four decision makers is presented to illustrate the use of the model and to demonstrate the capability of the model. The results show that the proposed model is a useful and effective decision-making tool for prefabrication adoption and optimization in concrete buildings.

1. Introduction

In concrete buildings, conventional on-site construction methods have long been criticized for long construction time, low productivity, poor safety records, and large quantities of waste [1,2]. Prefabrication can offer significant advantages, such as shortened construction time, improved quality, enhanced occupational health and safety, less construction site waste, less environmental emissions, and reduction of energy and water consumption [3,4]. Although the benefits of prefabrication have been well documented, in the United States, the market share of reinforced concrete construction supplied by precast producers is only 6% while the average across the European Union is 18%, and the prefabricated concrete system share of the overall building construction market is approximately 1.2% [5]. A major reason for the reluctance among decision makers to adopt prefabrication is that they have difficulty ascertaining the benefits such an approach would add to a project [6]. Indeed, prefabrication is not always the only available option, nor is it always better than on-site construction method due to various project characteristics and available resources. If not employed appropriately, change orders, severe delays in production, substantial cost overruns, and constructability problems may be encountered in the use of prefabrication.

Decision to use prefabrication based on familiarity and personal preferences is not uncommon [7]. Attesting to this, Pasquire and Connolly [6] demonstrated that the decision to include prefabrication is still largely based on anecdotal evidence rather than rigorous data, as no formal measurement strategies are available. Pasquire et al. [8] showed that insufficient attention is given to the discussions of whether or not to prefabricate a building or parts of a building. Recently, Blismas et al. [9] also indicated that holistic and methodical assessments of the prefabrication applicability to a particular project are lacking, and common methods of evaluation simply take material, labor and transportation costs into account when comparing various options. Accordingly, there is a need to provide a decision-making tool that would stimulate the appropriate discussion of the suitability of prefabrication and other construction methods for concrete buildings. We undertake this challenge, and in this paper, a solution is proposed as a response to this need.

2. Review of related decision-making tools

To develop a meaningful tool, an extensive review of literature in related areas was conducted including: modular construction, PPMOF (Prefabrication, Preassembly, Modularization, and Offsite Fabrication),

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prefabricated building components, structural frame selection, etc. The findings are summarized below.

In modular construction areas, Murtaza et al. developed MODEX [10], a DOS-based expert system, to aid in conducting the feasibility and economic analyses of modular construction for a power plant project. Later, based on MODEX, Neuromodex [11] was developed for construction modularization decision making using neural networks. For evaluating the use of PPMOF on particular projects, Song et al. [12] described a computerized tool to facilitate the decision-making process. The decision framework is divided into three levels. The first and second levels are designed to provide insight on the applicability of PPMOF based on primary drivers and impediments. The third level is focused on cost comparisons to determine feasibility and scope of PPMOF. Regarding prefabrication, IMMPREST toolkit [8] consisting of three tools: A, B, and C was developed to do comparative evaluations of traditional and prefabricated construction. Tool 'A' is designed to reinforce the user friendliness of the toolkit; tool 'B' is proposed to lead a strategic discussion on what is or isn't appropriate for prefabrication while evaluating the project drivers and constraints; and tool 'C' is used to carry out detailed evaluations of six relevant factors. For structural frame selection, Soetanto et al. [13] developed a simple framework using the importance of each criterion and the likely performance of various structural frame options. Luo [14] identified a list of generic prefabrication opportunities and tactics and developed a decision-making tool using dynamic programming analysis.

As summarize above, the decision-making tools for modularization, PPMOF, and prefabrication have been well documented. However, some limitations in these studies are also noted. For example, in MODEX tool, the DOS-based software would need to be updated for contemporary computer operating systems [12]. The use of the neural-network-based Neuromodex requires the availability of a large amount of historical data, and assumes that the past modularization decisions were correct [15]. In Song et al.'s research [12], the computerized tool is focused solely on the strategic level analysis, and the weight assignment to each category is subjective, which might be biasing. Although the IMMPREST [8] includes a comprehensive comparison between prefabrication and on-site construction method, the most significant challenge to use the toolkit is the limited information available at an early stage of a project. Indeed a follow-up survey ascertained this "Many of the items listed were not currently recorded in any meaningful way" [8]. Most importantly, all the above mentioned tools have failed to include both 'hard' and 'soft' performance attributes while evaluating different construction methods. Moreover, the inclusion of appropriate tools for multi-attribute problems under risk and uncertainty considerations is rare.

Construction method selection for concrete buildings is not a simple decision-making problem based on a single criterion. Decision makers have to look at various project-related factors (e.g., site characteristics, labor availability, etc.), identify their objectives (e.g., cost minimization, better safety records, etc.), and select an appropriate method — prefabrication, or conventional on-site construction. Thus, the construction method selection is a decision problem that can be characterized as a multi-attribute and multi-objective decision-making process.

In addition, construction method selection is a decision-making problem with a high degree of inherent uncertainty and risk. It is not possible to know exactly how a particular construction method will perform for a specific project until it is used. Hazelrigg [16] argued that design is always a matter of decision making under conditions of uncertainty and risk, and thus the issues need to be either considered formally or informally while analyzing a design problem. Accordingly, it is useful to explore a decision support tool that helps decision makers to articulate their objectives and attitudes towards risk in a way that can be used in decision making. One method that integrates uncertainty along with the risk attitude to make tradeoffs at various attribute levels is Multi-Attribute Utility Theory (MAUT).

MAUT has been widely applied to public sector since most problems in the field involve multiple conflicting objectives, such as in public health care systems, regulatory issues, etc. [17]. Despite the maturity of the method, limited applications of MAUT in engineering have been found. Airplane selection problem [18], staple product line selection [19], irrigation system evaluation [20], automobile manufacturer selection [21], and dismantling scenario for a reactor [22] are reported among engineering applications. MAUT application in the construction field is especially rare; we have found just one related paper, which is on appropriate construction contractor selection [23].

The objective of the paper is to develop an effective decision support tool that can assist project members to better evaluate construction methods for concrete buildings at early design stages, especially focusing on prefabrication adoption and prefabrication optimization. Not only should the tool include both 'hard' and 'soft' performance attributes that are usually available in conceptualization, the tool should also allow decision makers articulate their risk attitudes and uncertainty considerations while evaluating construction methods.

3. Multi-Attribute Utility Theory

Multi-Attribute Utility Theory (MAUT), developed by Keeney and Raiffa in 1976 [24], is used to rank alternatives or make a choice against two or more attributes based on expected utility theory. Expected utility theory states that if an appropriate utility is assigned to each possible consequence and the expected utility of each alternative is calculated, then the preferred decision is the option whose expected utility has the highest value. In this theoretical framework, the technique decomposes the multi-attribute utility function into a more practical form for elicitation based on a set of assumptions, namely preferential independence and utility independence [25]. The concept of utility independence can be viewed as a special condition of the concept of preferential independence [24]. This suggests that the preferential independence assumption is a weaker assumption than utility independence.

In MAUT, each alternative is assessed for desirability using a number of attributes. What connects the attribute scores with desirability is the utility function. Utility function is a device which quantifies the full range of uncertainty and the decision maker's attitude toward risk by assigning a numerical index to varying levels of criterion satisfaction [26]. Theoretically, there are three identifiable attitudes towards risk: risk averse, risk neutral, and risk prone. The decision maker's preference attitude is reflected in the shape of the utility curve.

The following seven steps describe the process of the MAUT application: (1) setting an objective and establishing attributes; (2) determining all possible alternatives; (3) determining the multi-attribute utility function form; (4) deriving the single utility functions for each attribute; (5) calculating the scaling constants in the multi-attribute utility function; (6) aggregating single utility functions; and (7) ranking the alternatives based on their aggregated utility value and making a choice. Each of these steps is discussed in detail in Section 4.2.

4. Construction method selection model

In this research, two prominent construction methods in concrete buildings are reviewed and discussed: on-site construction method and prefabrication. The framework of the construction method selection model (CMSM) is divided into two sequential levels: the strategic level (feasibility analysis) and the tactical level (detailed analysis), as shown in Fig. 1. Strategic level is conducted to initially evaluate the feasibility of prefabrication for a particular project using a concise list of questions. Tactical level is designed to evaluate to what extent building components should be prefabricated for the project based on sustainable performance attributes if the result of the former strategic level is prefabrication. The advantage of the two-step analysis approach is that decision makers don't need to spend a long time in one session to make a