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Development of decision-making tool for construction method selection: Choosing and optimizing offsite construction

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ABSTRACT

Offsite construction is considered as a possible solution for addressing time, quality and cost concerns associated with traditional construction method. Successful implementation of these methods on a particular project requires systematic analysis and early decision making based on specific factors of the project. There is a lack of an efficient systematic approach that can match the changing needs, deal with the growing complexity of building projects and take into consideration recently developed innovations, technologies and regulations. The objective of this study is the development of an early-phase decision tool to support construction project teams in selecting construction methods. This paper proposes a multi-level decision framework. The first level conducts a feasibility study and evaluates the applicability of offsite construction. The second level proposes an integrated approach for the decision-making problem that combines the Analytical Hierarchy Process (AHP) and the Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE). The combination of both approaches enables a careful evaluation of different construction methods and scenarios for the same project. A computerized tool is developed and tested on a case study to help a project team in the decision-making process.

KEYWORDS

Offsite construction, building construction method, decision making tool, multi-criteria decision making, modular construction, decision factors

INTRODUCTION

There are different construction methods and selecting an appropriate one from among the various existing alternatives is a challenging task. Selecting a construction method for buildings is not a simple decision problem based on a single criterion. Decision makers must consider various project factors (e.g., site characteristics, labor availability, etc.), determine their objectives (e.g., cost reduction, improved safety, etc.), Thus, the choice of construction method is a decision problem that can be characterized as a multi-attribute, multi-objective decision process. It is challenging to know exactly how a particular construction method will work for a specific project until it is used. Therefore, it is useful to provide a decision support tool that helps decision makers articulate their goals and attitudes toward risk in a way that can be used in decision making. Often in the literature, it is found that the choice of construction method is based on the opinion and experience of decision makers without taking a structured approach (Azhar et al., 2013) and (Pan et al., 2008a). These studies found a lack of historical data, poverty of formal measures, and lack of decision procedures. Blismas et al., (2005) present further evidence that decisions comparing traditional and off-site construction were largely based on material, labor, and transportation costs, while other cost-related elements, such as site facilities, crane use, and rework, were ignored. In addition, the same study stated that important issues such as health and safety, management impacts and process benefits were sometimes either implicit or ignored. Across the sector, the evaluation and selection of construction practices continue to be governed by a fragmented, cost-driven rather than value-driven culture. To overcome this construction industry barrier, several studies have laid the groundwork for the development of a decision support tool for construction method selection and assessing the feasibility of new construction methods and especially the feasibility of offsite construction. One of the first initiatives in the construction industry to develop a decision support tool was undertaken by the Construction Industry Institute (CII). In 1992, a first version of the tool called MODEX (Modularization Expert) was launched and designed as a decision support tool for the selection of the construction method for process and power plants (Gupta et al., 1996). One of the limitations of this tool is the way in which the result is "imposed" which prevents the decision maker from understanding which characteristics of the project most drive him towards the adoption of a certain construction method. Indeed, the user can only see the result without the possibility of interacting with the tool to gain knowledge about the drivers and obstacles of offsite work. In a subsequent study, Murtaza and Fisher, (1994) developed a more advanced tool called NeuroModex. This tool is based on a neural network architecture, which allows to process unstructured decisions by identifying interesting patterns through experience. They decided to go for a neural network since, in the construction sector, decisions are often made based on experience without weighting each decision factor separately. Validation of the method highlighted that NeuroModex is more accurate than the original MODEX. Cigolini and Castellano, (2002) developed a model that compares the overall project cost when a modular approach is chosen versus the conventional construction method for onshore plant construction projects. The main limitation of this model is the fact that it does not consider the costs of studies and engineering that are indispensable for successful off-site work. Song et al., (2005) developed a decision support system to compare offsite work with conventional manufacturing techniques. The objective of this tool was to help decision-makers at the front end of the process recognize the critical factors to consider when evaluating the adoption of offsite construction. However, the tool focuses solely on strategic analysis. In addition, the tool was developed over ten years ago with data from a 2002 study. Therefore, it may not adequately address the increasing complexity of recent market and industry developments, such as sustainability, green building, and the availability of new technologies such as BIM. Diez et al., (2007) developed a software system called AUTOMOD3. This system is mainly delimited in the sector of individual housing construction and has been commercialized in various projects in Spain and the Netherlands. In 2008, Pan et al., (2008b) developed a decision support matrix for the selection of construction methods for multi-family housing projects by enriching their tool with a database of offsite construction solutions. Pasquire et al., (2015) developed the IMMPREST toolbox which consists of three tools. It was designed to perform comparative evaluations of traditional and prefabricated construction. The biggest challenge in using this kit is the limited information available at an early stage of a project. Indeed, a follow-up survey found that "many of the items listed were not recorded in any meaningful way at this time." (Chen et al., 2010). Given the existing tools that help in selecting construction methods and comparing traditional and offsite construction, an improved approach is suggested in the form of a practical, computerized tool. In this context, the present study aims to contribute to the improvement of decision making in the design phase of construction method by introducing a new decision-making solution.

OBJECTIVES AND METHODOLOGY

The aim of this study is to develop a decision support tool that can assist construction stakeholders to achieve two objectives: First, to perform an off-site construction feasibility study. Second, to compare different construction solutions to select the most suitable one for the project. The computerized decision-making tool is developed using python programming language and graphical interfaces on Microsoft Excel for input data entry and results retrieval. A mix-methods design, which combines a literature review, questionnaire survey with 55 responses, and 10 semi-structured interviews and focus group was used to achieve the research objectives and ensure validity and reliability of the findings (see Figure1). The mixed research methods allow interrogation and triangulation of both quantitative and qualitative data (Zou et al., 2014). Previous researchers also adopted and highlighted the benefits of using mixed methods research design in the construction engineering and management field (Lau et al., 2019). Triangulation, simultaneously using multiple research methods is a valuable strategy in the research process, as mix methods will complement the strengths and weaknesses of other methods.

Level I: Feasibility study

This aims to initially evaluate the feasibility of offsite construction. It requires only minimum information, usually available at the early project stages. The first list of decision-making factors used at the strategic level is developed based on a literature review. Factors used in previous studies whose objective is to compare conventional and off-site construction are collected. They are then classified into categories. Identified factors were verified through face-to-face semi structured interviews with 10 participants that hold management and decision-making positions in different construction companies. The analyses of the interview transcripts helped to validate the list of factors found in literature. Next, a questionnaire survey was used to identify the importance of these factors from the point of view of French construction actors. From the results of the bibliography, the semi-structured interviews, and the questionnaires the final list of factors is developed. It consists of fifty-four secondary factors divided into seven categories (primary factors: planning, labor, design, site characteristics, organization, environment, and cost).

In the evaluation process decision-makers are first asked to assign weight factor values to each of seven primary factors. Then, for each category, the decision maker is asked to assess the impact of offsite construction more specifically by giving a score to each secondary factors. Secondary factors are evaluated based on the comparison of traditional construction with offsite construction. At the end of this step the user will get the following results: (1) An off-site construction score for the overall project and a score for each primary factor and (2) two lists of factors: One list containing the factors that support off-site construction and a second list containing the factors that do not support it.

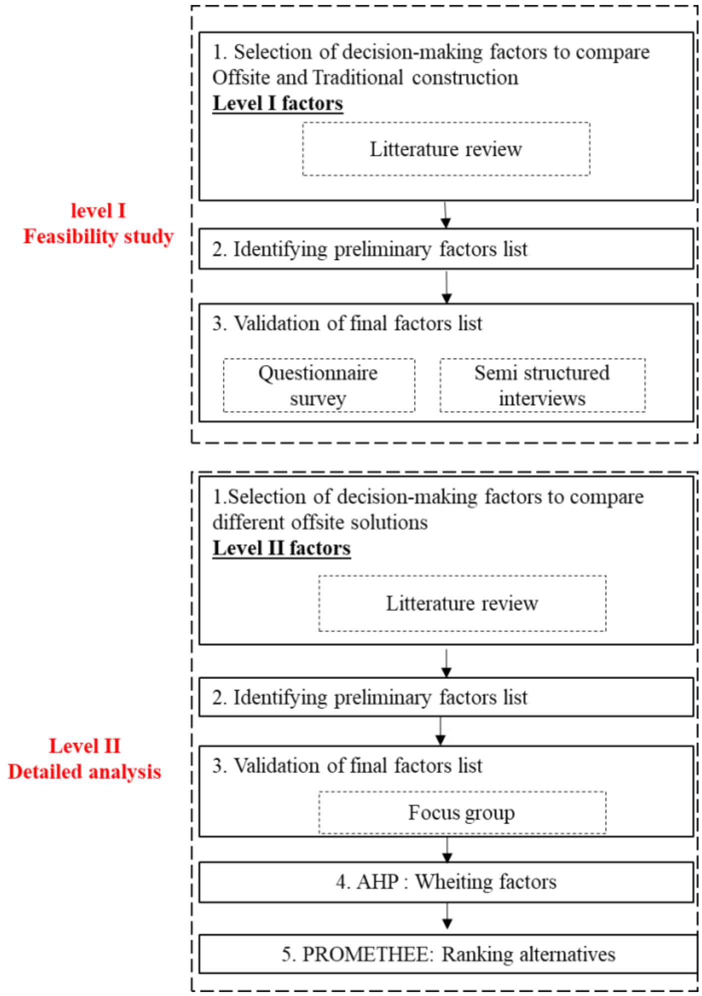

Figure 1: Research method followed to develop the decision-making tool

Level II: Detailed analysis

If industrialization through prefabrication is appropriate for the construction project in question, an analysis is required to determine the type of prefabrication suitable to maximize the efficiency of the construction method and achieve the project objectives.

This involves developing a hybrid model by combining two multi-criteria decision making (MCDM) methods, AHP (Analytic Hierarchy Process) and PROMETHEE II (Preference Ranking Organization Method for Enrichment Evaluations), to select the best construction solution. In this part of the study, a model with eight criteria is developed. The AHP method is used to calculate the weights of these criteria. Then, the best alternative is determined by the PROMETHEE II method using these weights. In defining the ranking factors, we worked closely with the potential decision makers by organizing a focus group. Eighteen factors are selected from the literature. To develop the final list of factors that meets the above conditions, the decision makers who participated in the focus group contributed to the reduction of this list through the selection of the most important factors. At the end of this focus group session the selected factors are environment, client acceptability, cost, construction complexity, planning, safety, repeatability, and supplier capacity.

Weighting of decision-making factors: AHP method
The choice of the appropriate construction method satisfying the different criteria of the different decision makers is a multi-criteria decision. The AHP method is used to solve this problem. It is considered as the most widely used effective method among the multi-criteria decision-making methods studied. AHP provides a practical approach to analyzing decision problems. It is a method for evaluating subjective and objective functions in multi-criteria decision making and helps users to reach an acceptable solution. It allows decision makers to check the consistency of their judgments. A higher value of the inconsistency index, i.e., greater than 0.10, should not be considered appropriate, and re-evaluation is required in these calculations (Saaty, 2008). AHP uses pairwise comparison of criteria to establish a priority or importance weight. The three steps of AHP are a decomposition into criteria, a comparative judgment of each against another and finally a synthesis in an aggregated form.

Ranking of different construction methods: PROMETHEE II method
For this step a ranking decision-making method called PROMETHEE is used. This decision making method is one of the recently developed MCDM methods which was first proposed by Brans in 1982 and further developed by Vincke and Brans in 1985 (Brans and Vincke, 1985). This method is a method for ranking a finite set of alternatives to be classified according to a set of criteria. PROMETHEE is also a ranking method that is quite simple in design and application compared to other MCDM methods, which has contributed to its rapid growth (Behzadian et al., 2009).

CASE STUDY

Decision making tool was tested by a project team that is working on a project called “BIOTOPE”. It is a 29300 m2 office building that will welcome 1400 agents of the European metropolis of Lille. It is made up of 8 floors and answers to 5 environmental certifications. The schedule is the main constraint of the project as it must be built in 19 months.

Level 1 results:
The test participant began by prioritizing factors. In this project the most important factor is schedule (weight = 5) due to the delivery constraint and the construction time of only 19 months. Followed by the design and structure of the building (weight = 4). Then comes the site factor and cost (weight = 3). The environment is ranked fifth (weight = 2) before labor and project organization given the various environmental certifications that the project must meet.
Table 1 presents the strategic level I first result. It provides a total score for off-site construction. As well as scores for each category of factors. The value of these scores varies between -5 and 5. A positive score means that the project conditions favor offsite construction. A negative score means that off-site construction, under the project conditions, is not the most suitable construction method. The overall score for offsite construction is equal to 1.57. This means that offsite construction is recommended. The main factors that favor offsite construction are (in decreasing order of importance): Design and structure of the project with a score equal to 2.80. Then schedule with a score equal to 2.29, followed by environment with a score equal to 2.20. Then labor and site characteristics with a score equal to 0.67 and finally the cost with a score equal to 0.4. However, in the context of this project, the project’s organization that describes the relationship with the various stakeholders does not favor off-site. This factor has a negative score of -1.

Table 1. Level I (Feasibility study) results

Factors	Factors weights	Percentage (%)	Score
Schedule	5	26.32	2.29
Labor	1	5.26	0.67
Project organization	1	5.26	-1.00
Environment	2	10.53	2.20
Site characteristics	3	15.79	0.67
Design and structure	4	21.05	2.80
Cost	3	15.79	0.40
Total project score			1.57

The second result provided by level I is the ranking of the 6 factors with the highest scores. These factors are motivations that favor offsite construction. These factors, their categories and their scores are presented in **Table *2***.

Table 2. Offsite construction drivers

Factor	Category	Score
Construction phase duration	Schedule	1,315
Design singularities	Design and structure	1,052
Repeatability	Design and structure	1,052
Waste management	Environment	0,526
Penalties	Schedule	0,526
Construction material delivery	Schedule	0,526

The third outcome of this level is the list of factors with the lowest scores. These factors present subjects that threaten the successful deployment of offsite construction. These factors, their categories and their scores are presented in Table 3.

Table 3. Offsite construction limitations

Factor	**Category**	**Score**
Site preparation	Site characteristics	-0.315
Seismic Conditions	Site characteristics	-0.315
Initial cost	Cost	-0.315
Exploitation & maintenance cost	Cost	-0.315
Project management cost	Cost	-0.315
Transportation cost	Cost	-0.315

Level II results

The decision-maker chose to test this level of the tool to compare two different solutions: Prefabricated and cast in situ elevator shafts.

First, he used the AHP method to weight the various factors. As shown in Figure 2, calculated factor's weights are 0.022 for environment, 0.033 for solution acceptability, 0.163 for cost, 0.082 for solution complexity, 0.343 for schedule, 0.055 for safety, 0.229 for repeatability, and 0.069 for supplier quality. AHP method also tests the consistency of the comparison made by the decision maker by calculating a consistency factor. This coefficient must not exceed the value 0.1.

In this application example, the coefficient d is equal to 0.095.

Table 4 shows the calculation of the score of alternatives using the PROMETHEE method. Based on this, we can obtain their ranking. The alternative with the highest score is the one that best meets the project objectives. In this case study alternative 2 (prefabricated elevator shafts) is the optimal solution for this decision-making problem.

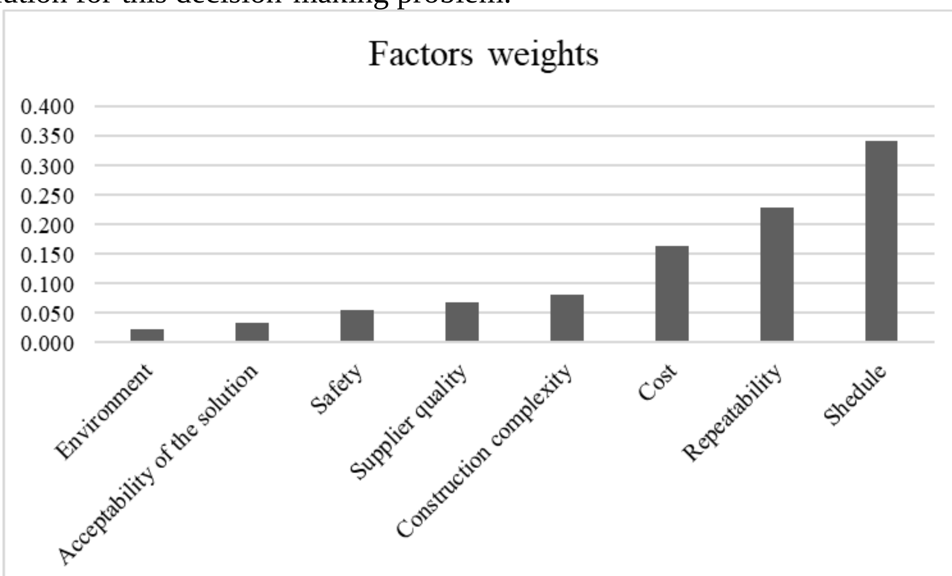

Figure 2. The difference in importance between the level II factors of the Biotope project

Table 4. score calculation and ranking of alternatives

Alternatives	**Scores**	**Ranking**
Cast in Situ elevator shafts	-0.474	2
Prefabricated elevator shafts	0.474	1

DECISION TOOL VALIDATION

Before the final construction of the tool described, the prototype of the tool was tested to determine whether potential users find it useful; what they see as its strengths and weaknesses; and what changes they suggest for improving it. The tool was tested on five different construction projects (mainly housing and office buildings). The test participants validated the usefulness of this decision support tool. They appreciated the clarity of the approach, the holistic aspect of the tool that allows them to address the problem of the selection of the construction method by sweeping different aspects such as economic, environmental, technical (design and structure), social (labor, relationship with stakeholders such as suppliers and customers). They validated that the results provided are consistent with the contexts of their projects. They also highlighted the tool's ability to assist them during the decision-making process in a structured way, and to help them document and justify their decisions.

The suggested points of improvement are mainly related to the ergonomics of the tool. They found that the first level is easier to use then the second level. It is mainly related to AHP method which requires filling a matrix (pairwise caparison) and checking consistency. As this is a first prototype, work on the ergonomics and the graphical interfaces will be done on the new version. The second point of improvement is the need to couple with the tool a database on different types of industrialized products.

CONCLUSION

The evaluation and selection of the choice of construction method remains focused solely on costs rather than on the value of the product itself. Criteria that objectively compare traditional and industrialized construction solutions are mainly material, labor and transportation costs. Very few project teams compare costs related to site facilities, optimized use of cranes, rework, environmental impact. In addition, issues such as worker health, site safety, administration and project management are either implicit or completely ignored. This paper is about a decision support tool that helps to select a construction method. It explains data collection method, the decision framework, the input data, the calculation methods and the output data. It is a tool that consists of two levels of decision making. The first level is intended to help users recognize the factors that need to be considered to make quick decisions about the use of offsite construction. It can also help identify drivers and barriers related to this construction method in the context of the project. The second level allows to select the most suitable construction solution. As a first step, it allows to compare the importance of the different factors to weight them in the most objective way possible, checking the consistency of the decision maker's judgment and finally ranking alternatives. The participants in the test of the tool validate its usefulness. It also helps to highlight important decision elements in the project delivery strategy. Considering offsite construction at the beginning of the project will allow the project team to "think offsite" from the beginning and provide special training and guidance to the design, planning, transportation, procurement, and construction teams. The tool can ensure that the project team is aligned through transparent, justified, and documented decision making. It encourages discussions on relevant topics and draws attention to hidden issues that, without anticipation, would lead to huge constraints during project execution.

The assignment of factor weights by the user is subjective, which is the main limitation of the tool. Another limitation that must be considered is the factors that have qualitative attributes such as the acceptability of the solution, quality, respect for the environment.

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