Article

Developing a BIM-based framework for supplier selection in Prefabrication

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Abstract: Improving the efficiency of the supply process in prefabricated components is challenging and requires accounting for a variety of risks involved in the management of the suppliers. The purpose of this study is to present a method to account for the systematic trade-offs between several supplier alternatives. A novel framework is presented for the whole assessment of supplier alternatives by taking advantage of the information extracted from customized building information modeling (BIM) and a database required for assessment of impacts. A data library related to assessment criteria for supply alternatives is built to facilitate the storage and sharing of information. Analytic hierarchy process (AHP) is used to select the optimal supplier that is able to provide the most satisfaction for the determined criteria. The proposed framework was also illustrated by the implementation in a mega project. The study implication is that BIM-enabled supplier selection can indeed lead to more benefits and higher values for all stakeholders.

Keywords: risk assessment; BIM; supply chain management; prefabricated construction products

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1. Introduction

Prefabrication is more like a manufacturing process, usually taking place at a specified plant where various materials are produced to be a component part of a final installation [1]. It is more of a means to increase efficiency where products, either standard or bespoke, are fabricated in a controlled manufacturing environment and assembled on jobsite. Compared with traditional building systems, prefabrication can bring numerous benefits such as lower cost, higher construction speed, reduced dependency on labor, increased productivity, improved quality and safety, and greater control over the construction process [2, 3]. Given the numerous advantages, prefabrication construction has been highly recognized by the global construction industry for 40 years [4]. In China, this technique has attracted wide public attention and has been supported by the "Made in China 2025" policy [5].

In view of its great benefits, industry decision makers have become increasingly interested in prefabrication and the possibility of its practical implementation [6]. Prior to making the decision, many aspects of prefabrication need to be thoroughly examined. The unique nature of prefabs requires effective management through the whole supply chain. Meanwhile, according to the findings of [7], the prefabrication supply chain is frequently impacted by many risks that impede the adoption of this technology. Supply chain management is complex because of the particular context of temporary multiple organization [8], the difficulties in managing the networks of numerous different firms that provide materials and multiple services [9, 10], and the challenges in relationship management [11].

Although the evolution of supply risks management process, the management of the risk is still greatly related with risks arising from improper supplier selection [12]. Project goals cannot be fully achieved without relying on the efficient suppliers working on the project [13]. Therefore, the selection of a suitable supplier is an important step to strengthen the application of prefabrication because the purchase of prefabricated products accounts for nearly 70% of the total project cost [14].

The selection of a supplier has a direct impact on the performance of a prefabrication project. Therefore, investigating the supplier selection problem is a means to mitigate overall risks. The old-style business norm that uses a single, simple criterion for competitive bidding is difficult to apply in this increasingly complex environment. A structured-frame method is required to help decision makers solve the complex selection problem.

Supplier selection is not a punctual act, it is usually a complex process. Various factors are critical to assess available suppliers [15]. If a supply alternative is the best option compared with all other alternatives, then selection is straightforward. However, this is rarely the case, and a number of alternatives usually exist where their relative performance may vary considerably against different criteria. In addition, due to the unique nature of construction projects and client preferences, different criteria may have different levels of importance, which should be accounted for in a real material supply selection process. Improving the efficiency of the selection process demands timely and effective information and a comprehensive analysis of the alternatives. This allow a multi-measure selection method to rank the alternatives depending on their aggregated performance against different criteria.

Criteria and measures were developed to be applicable to all suppliers considered and to reflect the company's requirements. It may not be easy to convert the requirements into useful criteria because needs are usually expressed as general qualitative concepts, while criteria are supposed to be specific measures that can be quantitatively evaluated. In general, developing criteria and measures should be practical to gather data and information. In this study, a set of criteria was developed to assess the supplier alternatives. The selection criteria and measures fall into one of five categories: final strength, product performance, support services, quality criteria and cost. In order to find the optimal option, the AHP (analytic hierarchy process) method is adopted. AHP was introduced in the 1980s by [16], and it is a powerful method for solving complex decision problems. It has been widely used in decision analysis in many fields, including management, real estate, sociology, economics, and business [17]. A pairwise comparison helps decision makers reach a comprehensive and practical judgment on complex decisions by considering a pair of measures one at a time. AHP is a mathematical method and can decompose the given problem into a goal and prepare the hierarchy of criteria and sub-criteria related to the goal. The bottom level sub-criteria of the hierarchy tend to be measurable, whereas the upper level criteria are rather difficult to measure. The AHP method was used in supplier selection to determine criteria weights and calculate supplier scores along with the criteria.

A proposed framework includes customized BIM and a comprehensive list of selection criteria is developed in this study to facilitate the supplier selection. BIM can be used to store data and information and then form the basis for decision-making [18]. Information plays an important role in decision-making, and poor quality information inevitably results in poor decision-making [19]. Moreover, BIM can also provide more details about the product due to its strength in modeling and visualization [20]. In addition, inputting the data into BIM helps decision makers see through various complexities and uncertainties. Using the innovated tools in the selection process, a comprehensive review of the supply alternatives will assist the design makers to choose the suitable suppliers. Moreover, BIM-enabled supplier selection process can also identify the underlying risks of the project, improve the quality of prefabs, and thus enhance the construction efficiency.

This paper is organized as follows. The following section is the literature review. The third section presents the proposed framework about the supplier selection. In the fourth section, the proposed framework is illustrated using a real mega project case. The fifth section provides the result and discussion. The study then concludes with the findings, contributions, and practical implications.

2. Literature Review

2.1 BIM

BIM is a powerful tool for prefabrication-based construction because of its physical and functional digital presentations [21]. It can be applied to physical projects, from buildings to bridges, at any stage, including planning, design, construction, operation, and maintenance [22]. Moreover, BIM has been used widely for prefabrication-based construction in many countries, such as the United States, the United Kingdom, Japan, South Korea, and Singapore [23, 24].

In performing a through literature review, BIM has been implicated at any stage of the process, from the project beginning to the final demolition stage, to improve information management. A series of studies and case studies have been focused on this area [25-30]. The application of BIM aims to enhance automation, reduce manual works and errors, and thus improve overall industry productivity. Moreover, some novel techniques were integrated into the BIM platform, such as laser scanning [31], RFID [32], GIS [33], VR [34], AR [35], and cloud computing [36], to improve project performance. In addition, to support important business, context ontologies and standard semantics have been adopted in software [37]. Currently, BIM is frequently used for production and cooperation of design information, while the usage of BIM in supply management, especially in supplier selection of prefabs, is not well known.

2.2 AHP

There have been many attempts to solve supplier selection problems consistent in multicriteria ranking of the suppliers. In [38], the study applied a simple additive weighting model to generate scores for each assessed supplier. In [39], the study addressed the benefits of fuzzy principal component analysis because it avoids multicollinearity among the criteria and eliminates errors of subjective weighting. In [40], the study decided to evaluate suppliers using TOPSIS in their integrated model for construction material management due to its computational simplicity, applicability in multicriteria analysis, and long tradition of adoption in construction-related decision-making. In [41], the study used AHP weight assessment criteria to rank the supplier alternatives.

2.3 Selection Criteria

In [42], the study indicated that prefabs can bring many benefits, but the delivery of prefabs is far from satisfactory. A reliable supply of required components plays a pivotal role in the continuity of workflow on construction sites, and projects can be stopped due to supply shortfalls. The late delivery can cause time and money overruns even result in project process stop. On this account it is justifiable to pay more attention to logistics process of prefab.

Several studies pointed out the desired attributes that suppliers are expected to fulfill, such as technological capability, financial health, and good services [43-47]. Many studies proposed to identify the criteria used by buyers to choose suppliers and concluded that quality, delivery, and product performance are the three most important [43, 44, 48-50]. On the other hand, the study conducted by [43] addressed how cost is regarded as the most important criterion followed by the good services provided. Base on the literature review the selection criteria were identified, as shown in Figure 1.

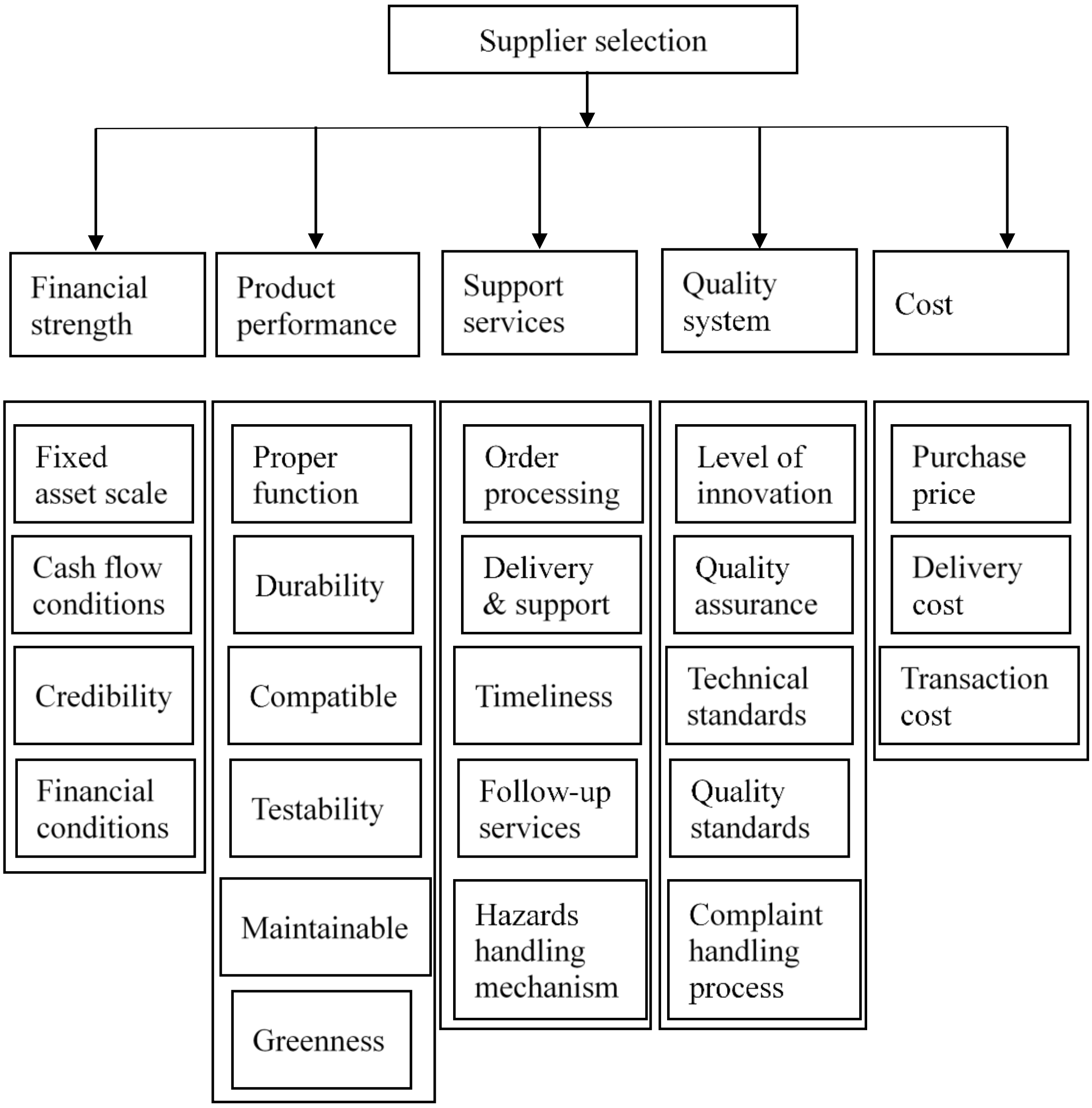

Figure 1. The hierarchy model for selection criteria

3. The Proposed Framework

The framework of decision analysis based on BIM for assessing supplier alternatives is shown in Figure 2. In the first step, the study prepared the required data for prefabs in the building sector by interview and accessible data and information from a pilot project (IBQ building in Beijing, China). Based on the required data and pilot project data, this study defined the required properties of prefabs, including geometry information, physical features, and mechanical requirements to assemble them. For the next step, the information is converted into a 3-D model by utilizing a BIM platform. Then, an optimization process is carried out to present the optimal size and location of prefab components. This will contribute to provide visualization of supplier alternatives and increase the attraction of BIM data at the decision process. Because prefabs data are used for evaluating the feasibility and performance, a comprehensive list of criteria was developed to assess supplier alternatives. The AHP method is used to comprehensively compare the characteristics of the suppliers.

3.1 Customized BIM

Upon the quantify assessment required, BIM is updated to incorporate a series of attributes of the supplier alternative for performance comparison. The attributes include tangible measures such as product specification and properties, intangible measures such as aesthetic described by linguistic terminology, and input parameters for modeling and management of the jobsite. Examples of this include construction equipment and logistic characters.

3.2 Selection of Assessment Criteria and Importance Weights

The function of the criteria database is to stipulate the selection criteria for the assessment of supplier alternatives and assign importance weights associated with each criterion based on client and contract preferences. Moreover, professional insights from project participants, such as architects, engineers, and contractors, should be accommodated into the criteria and selection process. Therefore, the criteria assessment was selected as an appropriate multi-measure method because it can help decision makers to identify potential requirement of the project and unforeseen risks.

The applicable assessment criteria for a project should be chosen based on project-specific requirements. For applicable purpose, each objective needs to be broken down into its constituted measures to better define the requirements. The assessment applies opinion survey to rank the selection criteria for the project to calculate the relative importance of criteria and rank the supply alternative against the criteria to generate the final score of each alternative. An option survey was conducted among the key project professionals, including client and senior managers, with influence on supplier selection.

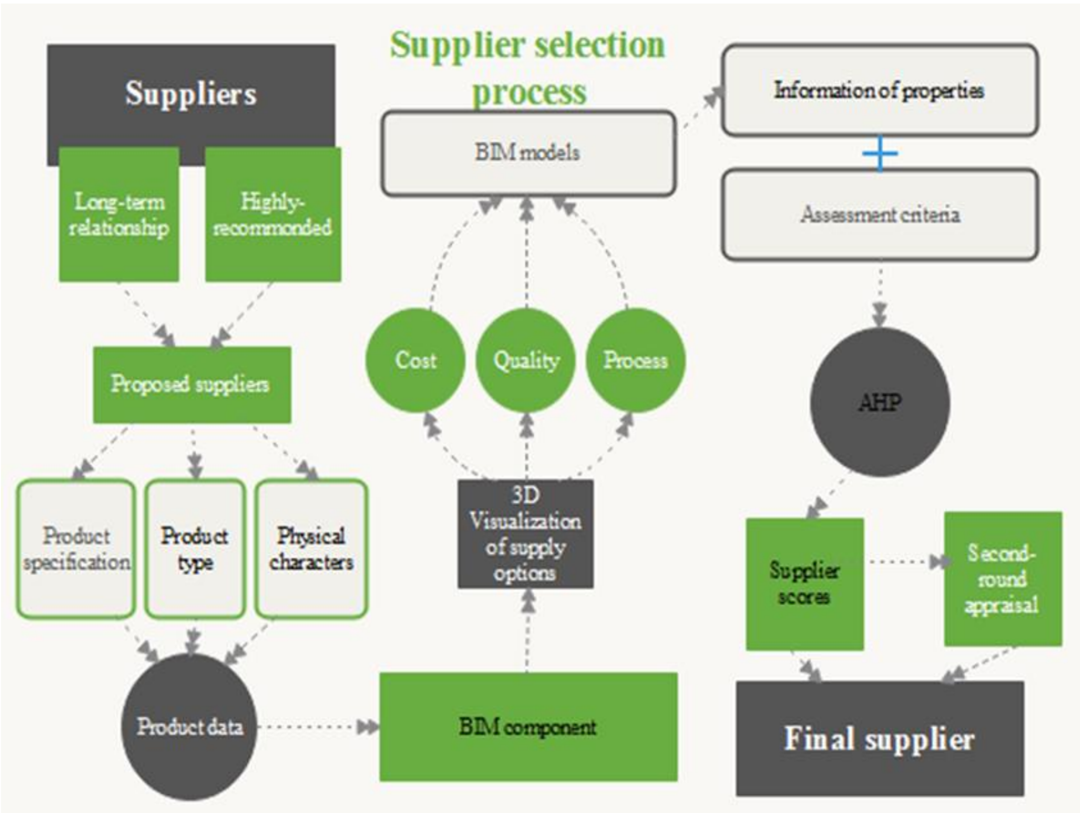

Figure 2. The framework of the selection process

3.3 The Relative Importance and Scores

In addition, the importance rank of the criteria may vary depending on the opinions of the project participants. A combination analysis was adopted to calculate the importance weights. First, the importance of each criterion was ranked by the selected key project professionals. A pairwise comparison—AHP—as an effective method was adopted for comparative analysis [51]. The opinions of the participants were collecting using a 1 to 5 Likert-type scale, where 1 represents "No importance" and 5 represents "Very important." Then, a pairwise comparison of all criteria generates a matrix used to obtain the criteria's priority matrix and priority vector. The summary of opinions on criteria is then computed through Equation (1).

$$RI_i = \frac{\sum R\times\omega}{h\times n}, \quad (1)$$

Where *RI* is relative importance of criterion *i*, *w* is rank scale assigned by each respondent, *h* is the highest scale (5 in this study), and *n* is the number of respondents. Further, the normalized relative importance was calculated using Equation (2).

$$NRI_i = \frac{RI_i}{\sum RI_i}, \quad (2)$$

To calculate the global importance of a criterion, the priority weight (D_i) generated from the pairwise calculation, was incorporated, as shown in Equation (3).

$$GI_i = D_i \times NRI_i, \quad (3)$$

The algorithm gives weight to each supply alternative based on which is the best option selected. In the AHP method, the weights of the criteria and the scores of the alternatives are calculated, which are called local proprieties. Then, the values of weights ω_i and scores γ_{ij} are aggregated by a weighted sum of the type, as shown in Equation (4).

$$S_j = \sum_i \omega_i \times \gamma_{ij}, \quad (4)$$

The global priorities S_j thus generated are then used for ranking the alternatives and selection of the optimal one.

4. Case Study

The application and benefits of the proposed framework are illustrated using a case study that includes material selection of prefabricated wall panels of a building project, as a representative building component of the project with significant effects on the supplier selection process. In other words, the proposed framework helps to decide on aspects of the procurement system related to identify the suitable products, the optimum supplier, and preferred logistics options.

The prefabrication project considered is a mixed-use apartment complex building, located in Beijing, China. This 17-story complex features spacious apartments above a ground floor retail space with a total floor area of 21,580 m^2 designed for service life of 100 years. The total surface area of the PC wall is approximately 11,180 m^2. The prefabricated wall panel is a load bearing element of the building that serves the primary function of support and transfer the building load, which considerably impact the building performance. The construction of prefabricated wall panels is usually regarded as the most important part of the project, in which a finish-to-start relationship is applied to every building level; thus, any delay encountered may delay the completion of the project. In addition, prefabricated wall panels can be made from a variety of steel and concrete, each with different properties and designs and thus different performance.

For the prefabrication project, one or more supply chain structure may be applicable. The option of a variety of prefabs, supply chain structures, and suppliers with different overlapping effects on the selection of the prefabricated wall renders the material selection highly challenging. First, the supplier alternatives for the case considered were modeled and organized according to the customized BIM. The BIM model for the project is shown in Figure 3. Then, the importance weights about the criteria and the scores of the supplier alternatives were attained from an opinion survey. The opinion survey was distributed among 28 key project professionals: two from the executive level, 16 from the management level, eight from contractors, one from the legal department, and one from marketing. This composition was determined by the involved professional have depth knowledge of project requirements as well as the familiarities to the potential suppliers.

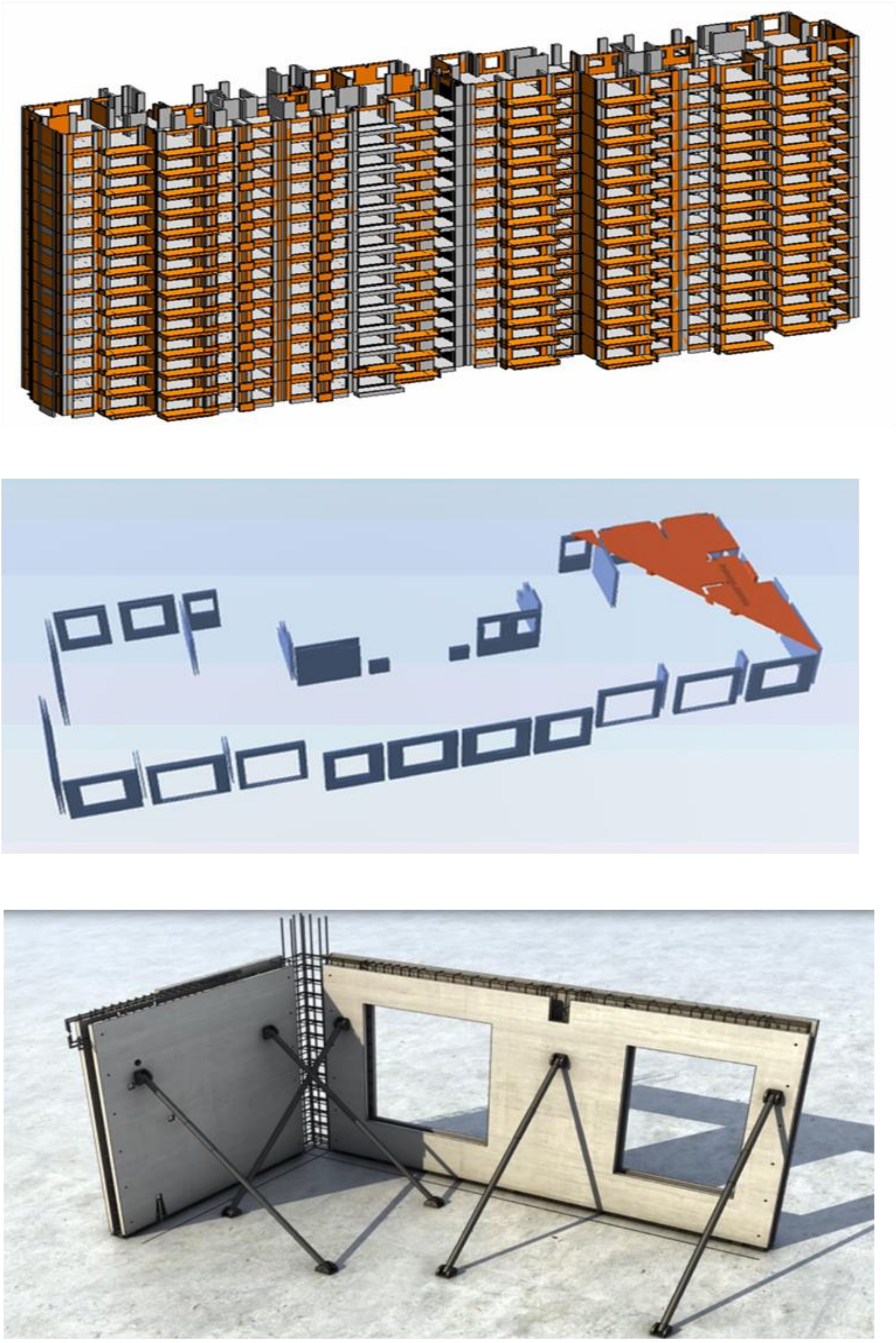

Figure 3. The BIM model for the case project

4.1 The Survey Details

1. Each criterion and potential supplier were scored on a scale of 1–5;

2. The relative importance of the criteria were calculated based on survey results from 28 project-related professionals, as shown in Table 1; the pairwise competition for the selection criteria is displayed in Table 2; and
3. The detailed information of the potential suppliers was investigated and ranked against the criteria by the 28 selected professionals.

The average score for each potential supplier against each criterion was then calculated, as shown in Table 3.

In this case, the project team identified several supply problems for this project. One of the most important issues is the continuous of the project process. If the prefabricated components cannot be timely delivery to the jobsite, then the project may not proceed, and this situation negatively affects project performance.

The AHP algorithm can be applied to a hierarchy model consisting of criteria, sub-criteria, and supply alternatives. The criteria for the supplier selection, the questionnaire results and their relative weights are shown in Table 3. As shown in Table 3, there are five criteria: financial strength, product performance, support services, quality system, and cost. Financial status is determined by fixed asset scale, cash flow conditions, credibility, and tax situation. Product function, durability, compatibility, testability, maintainability, and environmental friendliness provide a measure of product performance. Similarly, order processing, delivery and support, timeliness and effectiveness, follow-up service, and hazards handling mechanism are the sub-criteria to decide support services. Quality system is determined by the level of innovation, quality assurance, technical standards, quality standards, and complaint handling procedures. Finally, the cost is composed of purchase price, delivery cost, and transaction cost.

In the AHP method, decision makers are required to provide their preferences by using Equation (4). The scores thus obtained are finally used for ranking the alternatives and selection of the most suitable one.

Table 1. The relative importance of criteria

Criteria	Sub-factors	RI	NRI

Financial strength	Fixed asset scale	0.693	0.232
	Cash flow conditions	0.843	0.282
	Credibility	0.707	0.237
	Financial conditions	0.743	0.249
	Subtotal	0.746	0.250
Product performance	Proper function	0.886	0.204
	Durability	0.628	0.144
	Compactible	0.757	0.174
	Testability	0.730	0.168
	Maintainable	0.650	0.149
	Greenness	0.700	0.161
	Subtotal	0.725	0.167
Support services	Order processing	0.740	0.190
	Delivery & support	0.840	0.215
	Timeliness	0.840	0.215
	Follow-up services	0.760	0.195
	Hazard handling mechanism	0.720	0.185
	Subtotal	0.780	0.200
Quality system	Level of Innovation	0.680	0.205
	Quality assurance	0.630	0.190
	Technical standards	0.610	0.184
	Quality standards	0.690	0.208
	Complaint handling process	0.710	0.214
	Subtotal	0.664	0.200
Cost	Purchase price	0.870	0.351
	Delivery cost	0.830	0.335
	Transaction cost	0.780	0.315
	Subtotal	0.827	0.333

Table 2. The pairwise comparison example

Please compare the level of relative importance between criterion 1 and criterion 2								
1/5	**1/4**	**1/3**	**1/2**	**1**	**2**	**3**	**4**	**5**
Extremely less important than				Equally important to				Extremely more important than

	Financial strength	Product performance	Support services	Quality system	Cost
Financial strength		1/3	1/2	3	1/3
Product performance	3		1	4	1
Support services	2	1		4	1
Quality system	1/3	1/4	1/4		4
Cost	3	1	1	1/4	

Table 3. The scores of proposed suppliers

Criteria	**Score**			
	Supplier A	**Supplier B**	**Supplier C**	**Supplier D**
Financial strength	2.993	4.282	3.000	3.282
Product performance	3.268	3.545	2.993	5.000
Support services	2.415	4.246	3.019	2.400
Quality system	2.190	3.587	3.126	2.834
Cost	4.685	3.351	3.119	2.650
Global score	109.9	137.1	111.2	111.7

5. Result and Discussion

A typical prefabrication project may comprise a variety of components with different supply options. However, for illustrative purposes, the focus of the case project is on supply alternatives of the prefabricated wall panel. The supplier alternative for construction of the prefabricated wall panel required by the case project are listed in Table 2. As shown in Table 2, the resulting importance weights vary from 0.664 (for quality) to 0.827 (for cost), highlighting the significantly higher relative importance of cost implication in supply decisions.

The client has attempted to work with its long-term partners. The available prefabricated components and delivery options leads to four feasible alternatives for the supply of prefabricated wall panel. According to the proposed framework, BIM of the case project was modified to include the custom features requested for analysis of supply alternatives. Apart from added parameters, other important parameters, such as delivery details and construction requirements, were gathered and stored in relevant databases or libraries.

BIM software has a built-in tool that allows the user to add material properties for modeling. These material libraries with limited material properties are for visualization purposes only and are not suitable for the material selection and procurement process. The development of coherent BIM libraries has led to a novel application of BIM in prefabrication supplier management. Moreover, the data extracted from BIM models generated for each supply alternative through varying the input attributes can help key professionals rank the supply alternatives against the criteria.

The building data about the prefabs required extracted from BIM model are imported to the analysis platform developed in Microsoft Excel. Several alternatives should be included in the platform in order to select the optimal one. As stated in the proposed framework section, the adoption of a pairwise ranking method to determine the relative importance of criteria can minimize the bias caused by the inherent tendency of each party attempting to score high to factors related to their responsibility.

Upon the importance weights of the criteria, the data extracted from BIM models generated for each supplier option were imported to Microsoft Excel. Table 3 shows the resulting ranking of supply alternatives. As shown, the results suggest Supplier 2 is the most suitable option. Moreover, Supplier 4 has been highlighted as the supplier providing the best quality products. Supplier 1 appears to be the choice for lowest cost.

6. Conclusion

The proposed framework provides users with a supplier selection method to choose the most suitable supplier for a project and thus may benefit all parties involved in the project. A framework for assessment of supplier alternatives considers both project-specific factors and suppliers' characteristics, including financial status, product performance, support services, quality system and cost

A comprehensive list of selection measures was established as evaluation criteria for a hierarchy of considerations in selection process. Moreover, the prefab data of the available suppliers were modeled and organized by the customized BIM.

To better illustrate the method, the framework was applied to a case study that included the supply of a prefabricated wall panel in a project where potential suppliers were evaluated and scored according to the criteria. The presented results of the case study provided users with an insight into the important measures in consideration may have on ranking of the available suppliers. Although customized BIM modeling has been provided for supplier selection, the quality of results can still be improved by adding project-specific criteria.

On the one hand, BIM facilitates the supply selection process, while on the other hand the prefabricated components gain greatly in quality. All in all, the productivity in construction industry has been improved. With the help of BIM, the jobsite processes can be modeled and handed over to the manufacturers. The BIM model provides all the details of the prefabricated components that enables complex elements can be produced.

The proposed framework has two theoretical contributions: First, the method selecting the optimal supplier not only depends on the material type and specification but also other variables, such as financial status, support services, and quality system. Second, supplier selection is usually subjective, while attempts have been made to present a fuzzy method for assessment of the qualitative impacts associated with the supplier selection process. The practical contribution is that the framework and database form the basis for data exchange for different prefabrication projects.

The construction industry is generally regarded as a low information intensity industry compared with the manufacturing, banking, and finance industries. The production of prefabricated components primarily relies on 2-D drawings from designers and engineers. Nevertheless, projects are complex with many components, many often of customized design. The customized BIM incorporates the product attributes that facilitate the prefab production, and thus it improves efficiency in the construction process. Moreover, the BIM model of the prefab products also provides producers with more information by visualizing the detail of the products and identifying the risks.

Although the BIM-enabled automatic process of retrieving data will be realized in the future, the framework can support the initial supplier assessment. Future study will focus on parameterize selection criteria and put them into BIM for application in project management. Moreover, the prefabrication components logistic planning supported by BIM will be developed in future study.

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