Research on Identification and Classification of Risk Factors in China's Prefabricated Building Supply Chain

Xiaohan Lai*

College of Qinggong, Harbin University of Commerce, Harbin, Heilongjiang, 150006, China

*Corresponding author's e-mail:laixiaohan0115@gmail.com

Abstract. The benefits of prefabrication have been widely recognized in many regions. To meet the needs of green building, prefabricated construction has also been promoted in China. Supply chain management is considered key to the success of prefabrication projects. However, there has been no systematic study on the risk factors affecting the supply chain of prefabricated buildings in China. This study aims to improve awareness of risk management in the supply chain of prefabricated buildings in China by identifying and classifying the risk factors. Through a systematic literature review, this paper identified 36 risk factors and categorized them into five aspects: "factors related to process planning and operations" (12 factors), "factors related to technology and information" (6 factors), "factors related to stakeholders and collaboration" (9 factors), "factors related to policies and regulations" (5 factors), and "factors related to the environment" (4 factors). The research found that in previous studies, factors related to "process planning and operations" were mentioned the most and were thus considered very significant risk factors. Based on the Analytic Hierarchy Process, we calculated the weights of 36 indicators. Suggestions for the development of the prefabricated supply chain in China were proposed, including enhancing labor skill training and mass production of prefabricated products to control costs.

Keywords: Risk Factors; Prefabricated Construction; Supply Chain

1 Introduction

Prefabricated construction is a rapidly developing construction method in recent decades. Prefabricated construction is different from conventional construction process, with plenty of on-site operations transferred to factory. It has been proposed that the benefits of prefabrication outclass conventional construction, including cheaper initial cost, higher quality, time saving [1], advanced technique [2]and environmental protection [3]. Therefore, prefabrication has been introduced to many regions, such as the US, Australia, Hong Kong [4].

In China, the government is vigorously promoting prefabrication, as the construction industry contributes a large proportion of greenhouse gas production [5] and energy consumption [6]. However, the performance of prefabrication is not satisfied in China [7]. According to [8], one important underlying reason is that the concept of supply

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chain risk management in prefabrication in China is relatively lagged behind. Particularly, without full understanding of supply chain risk factors, it is difficult to achieve the performance of prefabricated construction primely [9]. However, previous studies rarely identified what risk factors will impact prefabrication supply chain in China [10]. Hence, this paper aims to enhance the understanding of risk management of prefabricated construction supply chain in China, through the identification and categorization of risk factors in the supply chain of prefabrication.

2 Previous Research on Prefabrication Construction Supply Chain

Prefabrication supply chain is considered more complex than conventional construction supply chain, as it includes the manufacturing process, transportation, storage and assembly of prefabricated components [11] concerning a great cooperation of contractors, suppliers, transporters and assembly subcontractors [12]. Over the last recent years, researchers have explored a number of risks factors involved the performance of prefabricated construction projects in various phases. For example, Lee and Kim [13] have reported plenty of risk factors about prefabrication, of which most were related to economy and market problems in prefabrication supply chain. Yang et al. [14] mainly focused on the risk factors in off-site logistic process of prefabrication supply chain, and they also adopted an uncertainty circle model to explain the effects of the identified factors. Liu et al. [15] assessed the supply chain management of prefabrication in China based on the visual angle of supplier in five aspects, and they put forward some models to analyze the maturity levels of each group. However, they investigated the only small portion of the supply chain of prefabrication, and they seldom claimed the specific risk factors of the whole supply chain in China.

3 A Risk Analysis Framework for Prefabrication Supply Chain

According the above literature review, it is found that previous researchers rarely adopted a systems perspective to explore prefabrication supply chain. Therefore, to have a better understanding of risk management of prefabrication supply chain, it is necessary to establish a systems framework to identify and analyze risk factors in prefabrication supply chain. In this paper, a risk analysis framework is provided to identify risk factors in the supply chain of prefabricated construction and categorize them under five aspects as Figure1: “process planning and operation-related factors”; “technology and information-related factors”; “stakeholder and collaboration-related factors”; “policy and regulation-related factors”; “environmental-related factors”. The five aspects together could powerfully reflect the complexity and dynamics of prefabrication supply chain system.

3.1 Process Planning and Operation-Related Factors.

The process planning and operation mainly aims at the management of internal operational systems, from design and planning, manufacturing, transportation, storage of prefab products to on-site construction. The risk factors in this category usually concern with human resources, material management and process control. For instance, the high direct material cost [16], lack of understanding of supply chain management [17] or lack of skillful crew in production process [18].

3.2 Technology and Information-Related Factors.

The technology and information involve the management of information and the proper application of equipment, automation and digital tools [5]. Machine breakdown [18] is a common technology problem during the construction project. On the other hand, data loss and misuse of machine [19], which would have a grave impact on the manufacturing quality and schedule, is also a source of risk.

3.3 Stakeholder and Collaboration-Related Factors.

The ability and collaboration between the upstream and the downstream serves as a significant part which might affect the performance of prefabricated construction during the whole supply chain [12]. The upstream primarily refers to the material suppliers, designers and contractors, and the downstream mainly include the transportation institutions, owner units and construction organization [2]. The risk factors in this category are mostly concerned with stakeholders' communication [4], and interorganizational collaboration [20].

3.4 Policy and Regulation -Related Factors

The policy and regulation generally consider design codes and standard direction in prefabrication industry [6]. For example, the lack of clear practical guidance and standards [17] would give rise to the quality problems. The alteration of policies and laws in government [21] could be regarded as another risk factor resulting in extra higher cost and time during the construction process.

3.5 Environmental-Related Factors

Environmental risk factors in this paper are seen as things beyond control, like the traffic jam which makes construction efficiency low [22]. In addition, Chen et al. [21] have found that natural disasters could severely cause the problem of construction conditions and the delay of production.

4 Methodology

To achieve the study goal, this paper adopted a literature review method, aiming for filling the gap that the unsystematic risk management of prefabrication supply chain in China. Literature review is considered suitable for this research, because it has been confirmed as an established and useful approach for pointing out the weaknesses and strengths of previous researches on theoretical stages [23] and identifying dependent literatures on a particular field. In this paper, the review process was conducted through two steps including data collection and data analysis.

4.1 Data Collection

In data collection stage, various databases were used such as google scholar, web of science, ScienceDirect, EBSCO and CNKI to collect all-related journal articles, conference papers and industry reports. In addition, Google engines are used to identify relevant industry and policy information to support this research. To guarantee the comprehensiveness and correctness of the risk factors, keywords are divided into three parts which included (1) prefabricated construction related ones such as "prefabrication", "offsite construction", "prefabricated building"; (2) supply chain related ones like "offsite logistics", "production", "transportation", "manufacturing" and (3) risk management related ones involved "uncertainty", "risk", "challenges", "barriers", "limitation", "critical failure factors".

To make sure the exactitude of search results, some standards are established to select helpful ones, and to eliminate useless ones. Particularly, articles which do not mention China and connect little with supply chain of prefabricated construction were deleted.

4.2 Data Analysis

In this step, qualitative content analysis is applied to analyze data through extracting and coding data and identifying topic based on the proposed five-aspect systems framework for prefabrication supply chain risk analysis. Similar views proposed by different authors were summarized and merged to one risk factor [3].

Statistic method is used to summarize the frequency and calculate the percentage of risk factors identified from 40 reviewed papers. The frequency indicates how important the risk factor is in the prefabrication supply chain [3]. In this research, factors with frequency over 70% are considered as "very significant" factors; between 50% and 70% are considered as "significant" factors; under 50% are considered as "less significant" factors.

5 Results and Analyses

36 factors were finally identified and categorized into five aspects, including "process

planning and operation-related factors" (12 factors), "technology and information-related factors" (6 factors), "stakeholder and collaboration-related factors" (9 factors), "policy and regulation-related factors" (5 factors) and "environmental-related factors" (4 factors). All the identified factors are illustrated in Table 1 and explained as below. In terms of numbers, "process planning and operation-related factors" were the mostly mentioned by previous research. According to frequency, three factors were considered "very significant": (1) high material, storage and transportation cost and other extra expenses, (2) lack of skillful designers and workers in factory and on site and (3) lack of uniform design codes.

Table 1. risk factors in prefabrication of supply chain in China

Category	Factors	F*	P**
Process planning and operation	• High material, storage and transportation cost and other extra expenses	33	0.83
	• Material damage or shortage in production and assembly process	14	0.35
	• Lack of skillful designers and workers in factory and on site	30	0.75
	• Delay due to long-distance transportation of prefabs	18	0.45
	• Lack of project planning and scheduling	23	0.58
	• Managers lack of understanding of supply chain management	20	0.50
	• Prefabricated components are not stored properly	13	0.33
	• Poor layout management in both the factory and the construction site	17	0.43
	• Inadequate supply chain performance measurement systems	11	0.28
	• Unreasonable and inflexible supply chain structure	14	0.35
	• Late design changes after production commences	24	0.60
	• Ineffective manufacturing process design	27	0.68
Technology and information	• Machine repairing and maintenance	12	0.30
	• Wrong operation and machine breakdown in assembly and production	27	0.68
	• Data loss and misuse	8	0.20
	• The adoption of emerging technologies such as robotics	19	0.48
	• Poor production technology	23	0.58

Category	Factors	F*	P**
	• Poor adaptability of equipment used in factory or on site	9	0.23
Stakeholder and collaboration	• Stakeholders have inconsistent business goals	16	0.40
	• Lack of knowledge and information sharing within stakeholders	27	0.68
	• Lack of supplier selection methods and frameworks	23	0.58
	• Clients/suppliers have inconsistent understanding of quality acceptance level	16	0.40
	• Lack of long-term partnerships and trust	13	0.33
	• Lack of experienced professionals and consultants supporting production	17	0.43
	• Construction enterprises cannot adapt the requirements of prefabrication	9	0.23
	• Contractors have poor experience on supply chain management	15	0.38
	• Long lead-in time for decision-making in the early stage	7	0.18
Policy and regulation	• Lack of clear practical guidance and regulations	24	0.60
	• Inadequate quality assurance and control system	26	0.65
	• Lack of uniform design codes	31	0.78
	• Poor official assessment system for prefabrication results	14	0.35
	• Insufficient government policy support	23	0.58
Environmental	• Traffic jam and accident during transportation	16	0.40
	• Covid-19	1	0.03
	• Clients' low adoption in prefabrication	13	0.33
	• The scale of the China market	19	0.48

**Notes: F= Frequency, P=Percentage

5.1 Process Planning and Operation-Related Factors

Most supply chain risk factors of prefabrication projects in China were found related to process planning and operation. This is mainly because prefabrication is still in its early stage in China and the industry does not have enough knowledge about prefabrication supply chain management, particularly in three aspects: (1) human resource management; (2) process management; (3) cost management.

Firstly, regarding human resource management, the "very significant" factor is lack of skillful designers and workers in factory and on site [13,20]. The possible reason leading to this problem might be a declining and aging population and lack of training.

Secondly, process management also can be problematic, such as ineffective manufacturing process design [16] and late design changes after production commences [10]. Another case investigated by Luo et al. [8] indicated wall leakage caused by poor sealing joint.

Thirdly, cost-related factors are widely considered as major risk factors in the management of production process, as prefabrication is supposed more expensive than conventional construction [9]. Identified sources of overhead costs in China include storage of prefabricated elements [10], machine repairing and maintenance [18], and initial material cost [20].

5.2 Technology and Information-Related Factors

The typical failure factor in technology aspect is wrong operation and machine breakdown in production and assembly [18]. Furthermore, the construction industry in China is promoting digitalization to achieve sustainable and green construction. Automation technologies such as robotics can be used in factory for efficient production of prefab products. However, the adoption of such new technologies can be technically challenging and financially risky.

5.3 Stakeholder and Collaboration-Related Factors

Prefab manufacturers and suppliers play an important role in prefabrication projects [10]. However, the literature review found that the reliability of prefabrication suppliers in China remains low while there is no comprehensive system or framework for supplier selection [24].

In addition, contractors often take charge the design and construction process which include a lot of messages passing and design problems, so lack of knowledge and information sharing within stakeholders might cause enormous losses [17].

5.4 Policy and Regulation-Related Factors

The design process in prefabrication is much more complex than that in conventional construction. Hence, lack of uniform design codes is found as one of the "very significant" risk factors.

Another significant risk factor is the application of inadequate quality assurance and control system [25]. Currently, there is no established standards or guidance from relevant government departments to guide the quality assurance and control execution in prefab factory [26].

5.5 Environmental-Related Factors

Traffic problems like traffic jam and accidents could cause the transportation delay. Furthermore, challenges for construction industry in China also concern as fellows: (1) clients' low adoption in prefabrication and (2) the scale of the China market. It is noticeable that the production and logistics of prefab is heavily impacted by Covid-19.

6 Weight Calculation of Supply Chain Risk Factors Based on AHP

American operations researcher T L. Saaty proposed The Analytic Hierarchy Process (AHP) in the mid-1970s, which is a multi-objective decision analysis method that is good at organizing and hierarchizing complex problems. AHP combines qualitative and quantitative analysis, using the experience of decision-makers to determine the relative importance between the standards for measuring whether each indicator can be achieved, and reasonably assigns values to each indicator element. By using the assignment data to determine the priority order of each scheme, it can effectively apply to problems that are difficult to solve with quantitative analysis methods. The basic idea of AHP is to treat the research object as a system, dividing it into different hierarchical structures in the order of target layer, criterion layer, and scheme layer. Based on subjective judgments of certain objective reality, the indicator elements listed in the structural model are quantitatively described layer by layer through pairwise comparison of importance. The basic process is shown in Figure 1.

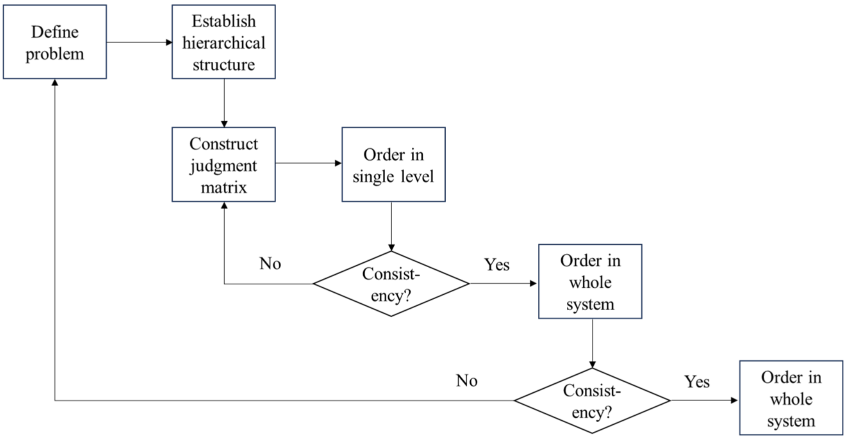

Fig. 1. Work program diagram of AHP

1. Establish a hierarchical structure model. Based on the investigation and analysis of the research problem and a large number of literature reading, the index elements related to the research problem are decomposed into several levels from top to bottom

according to different attributes, and the index elements in the same level are subordinate to or have an impact on the index elements in the upper level. At the same time, it dominates the index elements of the next layer or is influenced by the index elements of the next layer. The top layer is the target layer, which usually has only one indicator element, and the bottom layer is the scheme layer.

2. Construct the judgment matrix. Starting from the second layer of the hierarchical structure model, for the elements of the same layer belonging to (or affecting) each index element of the upper layer, a judgment matrix is constructed by using the pairwise comparison method to evaluate the importance of each related element in the layer relative to an element in the upper layer. It is of the form: suppose the upper level element criterion is AK, which is suitable for the next level elements B_1, B_2, … , B_n have a dominant relation, and the elements B_1, B_2, … , B_n . For any judgment matrix, it should satisfy: bij > 0; bii = 1; bij = 1/bji (where I, J = 1,2, … , n).

3. Single-level weight vector calculation and consistency check. The purpose of single-level ranking is to determine the weight value of the importance order of each element related to an element in the previous level. The actual operation process can be attributed to the problem of calculating the eigenvalues and eigenvectors of the judgment matrix. In this paper, the simple and effective sum-product method (ANC) is used to calculate. Taking the W judgment matrix A as an example, the specific steps are as follows: First, the elements of each column of the judgment matrix are normalized, and the general terms of the elements are:

$$\overline{b_{ij}} = \frac{b_{ij}}{\sum_{k=1}^{n} b_{kj}} (i, j = 1,2, \cdots, n) \tag{1}$$

Secondly, the judgment matrix of each column after normalization is added by row as follows:

$$W_i'' = \sum_{j=1}^{n} \overline{b_{ij}} \, (i, j = 1,2, \cdots, n) \tag{2}$$

Weight is obtained after normalization

$$W_i'' = \frac{w_i''}{\sum_{j=1}^{n} w_i''} \tag{3}$$

Before ranking, it is necessary to check the consistency of the judgment matrix results. If the test result is passed, the feature vector (after normalization) is the weight vector; if the test result is not passed, the pairwise comparison matrix needs to be reconstructed, and the test process is as follows.

First, the largest eigenvalue of the judgment matrix is calculated.λ_{max}

$$\lambda_{max} = \sum_{i=1}^{n} \frac{(AW)_i}{nW_i} \tag{4}$$

Secondly, calculate the Consistency Index (CI):

When CI = 0, the judgment matrix has complete consistency; Conversely, the larger the CI is, the worse the consistency of the judgment matrix is. When the order n of the judgment matrix is greater than two, it is necessary to compare CI with the average

Random Index (RI) which is called the Random Consistency Ratio (CR) of the judgment matrix.

$$CI = \frac{\lambda_{max} - n}{n-1} \quad (5)$$

$$CR = \frac{CI}{RI} \quad (6)$$

4. Calculate the weight vector of the comprehensive hierarchy and check the consistency. Comprehensive hierarchy sorting is to use the results of single sorting of all hierarchies in the same hierarchy to calculate the importance weight values of all elements in the hierarchy for the previous hierarchy. In order to evaluate the consistency of the calculation results of the comprehensive hierarchical ranking, the consistency test is also needed. When CR < 0.1, it is considered that the calculation results of hierarchical total ranking pass the consistency test; Otherwise, each judgment matrix of this level needs to be further adjusted.

Based on AHP, we calculated the weights of 36 indicators, which is shown in Table 2.

Table 2. Weights of 36 indicators based on AHP

Category	Factors	Weight
Process planning and operation	High material, storage and transportation cost and other extra expenses	0.022
	Material damage or shortage in production and assembly process	0.030
	Lack of skillful designers and workers in factory and on site	0.047
	Delay due to long-distance transportation of prefabs	0.015
	Lack of project planning and scheduling	0.014
	Managers lack of understanding of supply chain management	0.045
	Prefabricated components are not stored properly	0.014
	Poor layout management in both the factory and the construction site	0.034
	Inadequate supply chain performance measurement systems	0.015
	Unreasonable and inflexible supply chain structure	0.028
	Late design changes after production commences	0.013
	Ineffective manufacturing process design	0.044
Technology and information	Machine repairing and maintenance	0.019
	Wrong operation and machine breakdown in assembly and production	0.047

	Data loss and misuse	0.017
	The adoption of emerging technologies such as robotics	0.021
	Poor production technology	0.063
	Poor adaptability of equipment used in factory or on site	0.040
Stakeholder and collaboration	Stakeholders have inconsistent business goals	0.012
	Lack of knowledge and information sharing within stakeholders	0.035
	Lack of supplier selection methods and frameworks	0.029
	Clients/suppliers have inconsistent understanding of quality acceptance level	0.020
	Lack of long-term partnerships and trust	0.011
	Lack of experienced professionals and consultants supporting production	0.008
	Construction enterprises cannot adapt the requirements of prefabrication	0.008
	Contractors have poor experience on supply chain management	0.011
	Long lead-in time for decision-making in the early stage	0.034
Policy and regulation	Lack of clear practical guidance and regulations	0.024
	Inadequate quality assurance and control system	0.042
	Lack of uniform design codes	0.051
	Poor official assessment system for prefabrication results	0.009
	Insufficient government policy support	0.015
Environmental	Traffic jam and accident during transportation	0.045
	Covid-19	0.036
	Clients' low adoption in prefabrication	0.055
	The scale of the China market	0.027

7 Conclusion

This study identified 36 risk factors that could affect the prefabrication supply chain in China through literature review. A systems framework was proposed to categorize the identified risk factors into five aspects. The main findings and recommendations of this research are summarized as follows.

Firstly, the workers and cost related factors are considered as the most significant risk factors. It is suggested that more training for labors could be provided to make them learn more skills about prefab manufacturing and assembly. Furthermore, the government could integrate the knowledge of prefabrication into higher education and develop students' professional knowledge in advance. In cost aspect, mass production should be promoted for cost control. Specifically, we could also enhance the standardization of components and expand the batch to reduce the cost.

Secondly, collaboration plays a primary role in prefabrication supply chain. Thus, we should build collaboration platforms for stakeholders (especially contractors and suppliers) for better communication and collaboration. In addition, the government could take the leadership to organize industry workshop and seminars with stakeholders for a better understanding of industry needs.

Thirdly, government can unify design and construction method, so as to improve the design codes of prefabrication. Financial incentives can be provided to promote the adoption of prefabrication.

Future research is needed to address the following issues. First, the significance of the risk factors could be further evaluated through interviews and questionnaire survey. Furthermore, study with real-life cases will be helpful to understand how the risk factors are controlled and managed.

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