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Developing a Fuzzy Multi-Criteria Evaluation Model for Prefabrication Development Maturity of Construction Firms

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ABSTRACT Prefabricated construction (PC) is considered as a sustainable construction mode that can improve project performance such as quality and efficiency. Even though, Chinese governments at different levels have formulated many guidelines and incentives to help construction firms better implement PC, their implementing PC level is still low. To some extent, this is likely attributed to ineffective measures of improving PC projects' performance for construction firms lacking adequate understanding of their PC development level and corresponding influencing factors. Furthermore, there are relatively scant research works exploring the issue. Thus, this study aims to formulate a PC maturity model that can be used to evaluate the PC development level of construction firms. It is also expected that this model can identify the key factors that influence the development maturity. The model is firstly established using a four-step methodology, namely, maturity dimension determination, maturity-associated criteria identification, criteria weights calculation based on Entropy and Fuzzy Analytical Hierarchy Process (FAHP), and maturity level evaluation based on fuzzy integral. Next, three construction firms are selected as study cases to test the model's effect on mapping out PC maturity and key influencing factors. Key findings are eventually analysed to derive effective strategies for improving the maturity of construction firms, further expediting the sustainable transition of the construction sector into PC.

INDEX TERMS Prefabricated construction (PC), multi-criteria evaluation model, development maturity, fuzzy integral.

I. INTRODUCTION

The construction sector is important to China's economic and social development [1]. However, the Chinese construction sector suffers from low efficiency, cost overrun, poor quality, high energy consumption, and environmental pollution problems[2]. In recent years, prefabricated construction (PC) has gained popularity among industry practitioners, and has been considered as an effective solution for improving the performance of construction sector. PC, also known as off-site, industrialised or precast construction, is a construction mode that allows precast concrete to be cured off-site under ideal conditions within the manufacturing plant, and be shipped to the job site for assemblying into the desired structure [3]. PC has a series of potential advantages such as higher efficiency, quality and worker safety [4], [5], and has already been a common practice in Western developed countries including Japan, Singapore, Australia, and so on [6], [7]. In recent years, a lot of effort has been made by Chinese governments at different levels to promote the use of PC [8]. However, the current uptake of PC by the Chinese construction sector is still far from proportionate to this dedicated effort.

Previous research has explored various measures of promoting PC development from different perspectives such as configuring PC product properties[6], quantifying PC project performance[9], eliminating PC constraints [7], and refining managerial processes [10]. However, the development level of PC stakeholders has been frequently overlooked. It is important for stakeholders to make effective measures to improve their performance of PC projects. PC stakeholders mainly include the client, project sponsor, project manager,

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members of the project team, technical and financial services providers, internal or external material suppliers, site personnel, general contractors and subcontractors, as well as end-users [11], [12].

Among these stakeholders, general contractors, typically known as construction firms, are playing an important role in PC development [13]–[15]. This is because general contractors oversee the construction of building works throughout the project, and are mainly responsible for project performance such as quality, cost, and duration [7]. Understanding PC development level is key to formulate effective measures to improve their PC project performance. According to [1], [13], [16], defining a maturity model is a method for evaluating the development level of a technology or management system adopted by an organisation. It has been used to address a wide range of issues in construction management such as Building Information Modelling (BIM) maturity [17], project management maturity [16], supply chain management maturity [18], risk management maturity [13], and knowledge management maturity [19].

A maturity model of PC development would thus be useful for construction firms to explore their level of PC development, further improving their PC projects' performance. In fact, previous research works that targeted on PC performance improvement from the perspective of construction firms are ample. These works mainly paid more attention to identifying drivers and barriers of PC development [7], [20], and exploring collaborative relationships among stakeholders [11], [21]. However, the evaluation of PC development maturity for construction firms has been overlooked.

To close these knowledge gaps, this study aims to develop a fuzzy integral based multi-criteria model that can be used to evaluate the PC development maturity of construction firms. Furthermore, key factors affecting the maturity level can be identified based on the model, which provides valuable references to make effective measures for increasing PC development maturity. The contribution of this study is four-fold. First, a fuzzy integral method is proposed to quantitatively evaluate the PC maturity of construction firms. Second, through a systematic analysis, a criteria system involving technology, operation management, sustainability, and economy for PC maturity evaluation is formulated. Third, a method integrating Fuzzy Analytical Hierarchy Process (FAHP) and Entropy is put forward to weigh the criteria. Four, critical PC maturity influencing factors are determined.

The research framework is depicted in Figure 1. The remainder of this paper is organised as follows: Section 2 illustrates the literature review on the construction industry maturity and maturity evaluation methods; Section 3 presents the specific maturity evaluation model including fuzzy integral, evaluation criteria, and maturity levels; Section 4 describes three study cases oriented calculated processes of the model; Section 5 analyses and discusses the results about maturity level and critical influencing factors; Section 6 sets out the limitations and future work of this study.

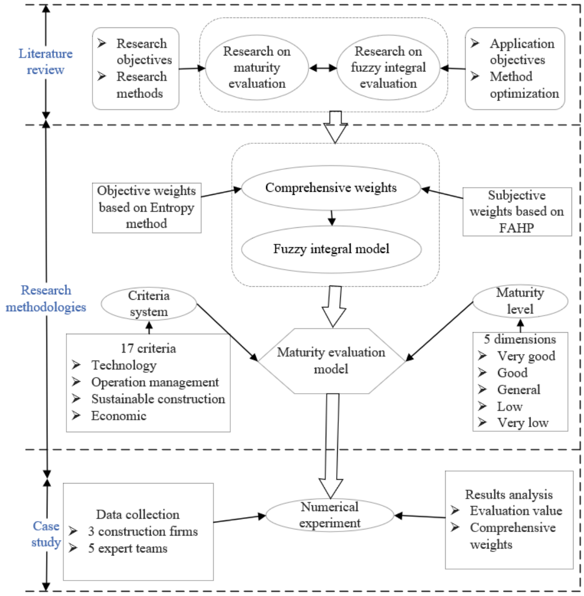

FIGURE 1. **Research framework.**

II. LITERATURE REVIEW

A. PC MATURITY IN CONSTRUCTION OVERVIEW

Maturity is an important aspect to reflect the current capability and development of one organisation in developing and applying technology [22], [23]. Maturity was first provided and used in the software engineering sector [22]. Since then, it was introduced into other sectors such as manufacturing [24], science and technology [25], [26], and medical service [27].

In fact, some previous research works have already focused on maturity in the construction sector for improving the performance of construction projects. Especially, there also has been research on PC-oriented maturity for improving PC projects' performance from different angles. Exiting literature include various topics such as supply chain maturity [18], construction industrialisation development level [28], industrialised construction capability [29], BIM maturity, and prefabrication capability maturity [30]. These have provided valuable information for construction firms to take measures of enhancing their PC capability, further improving their projects' performance. For example, Kangning *et al.* [18] provided a path of enhancing the PC project's performance of the main contractor through evaluating the maturity of supply chain management.

Notably, it is more useful for construction firms to undertake effective and systematic measures with a clear understanding of their holistic development maturity and influencing factors [1]. However, there is relatively scant research focusing on evaluating the maturity and identifying the factors, resulting in negative effects on making measures and the improvement of PC capability. Thus, this study focuses on this issue by providing a multi-criteria fuzzy evaluation model.

B. EVALUATING METHODS OF MATURITY

Maturity models are used to evaluate the maturity, as well as provide directions of improvement [18]. There are a number of maturity models that have been developed in various contexts, including but not limited to Capability Maturity Model (CMM), Project Management Maturity Model (PM3), and Process Maturity Model (PMM) [31], [32]. The evaluation method is an essential component of maturity model, and has a critical impact on the model's calculated result [30]. Often, the mean method was adopted in previous research [33]. However, this method was based on a questionnaire, which was complicated and difficult to undertake. Additionally, some multiple-criteria decision making (MCDM) evaluation methods such as Analytical Hierarchy Process (AHP), data envelopment analysis (DEA), and TOPSIS [34], [35] were adopted. However, these methods mostly rely on survey-based subjective data of criteria, and overlook the objectivity of the factors, which may has a negative impact on the accuracy of evaluation results [36].

Fuzzy integral is a multi-criteria evaluation method that can fufill comprehensive evaluation based on both subjective and objective criteria's data[37]. The fuzzy integral method has been effectively utilised in a range of research areas, such as evaluating suppliers [35], performance [38], products [34], and projects [39]. For example, Wen-Shing [40] developed a fuzzy integral method to evaluate the energy performance of buildings, and provided an effective method for energy performance evaluation.

Moreover, fuzzy integral has been integrated with other methods to improve the accuracy of calculated results. Especially, some effective methods calculated criteria' weights, e.g., Analytic Network Process (ANP), AHP and FAHP, were adopted to optimise the calculation of criteria' weights. For example, James *et al.* [35] provided a nonadditive fuzzy integral method for supplier evaluation, determining criterion weights based on ANP, improving the accuracy and decreasing the complexity of calculation. These studies have obtained good performance for evaluating the maturity. However, there have been very few research works comprehensively considering the objective and subjective aspects of evaluation criteria in calculating the criterion weights.

Generally, FAHP and AHP are subjective evaluation methods through considering vague evaluation data collected from experts [41], [42]. Entropy is an objective evaluation method based on the practical value of criteria [43], [44]. Integration of FAHP, AHP, and entropy is proven to be a more effective and comprehensive method for calculating weights. Especially, an AHP-Entropy method has been developed to evaluate the environmental management maturity level[32], as well as the construction industrialisation development of construction firms [29]. A FAHP-entropy method has also been utilised in evaluating issues with more practical and effective results than AHP-Entropy [36], [45].

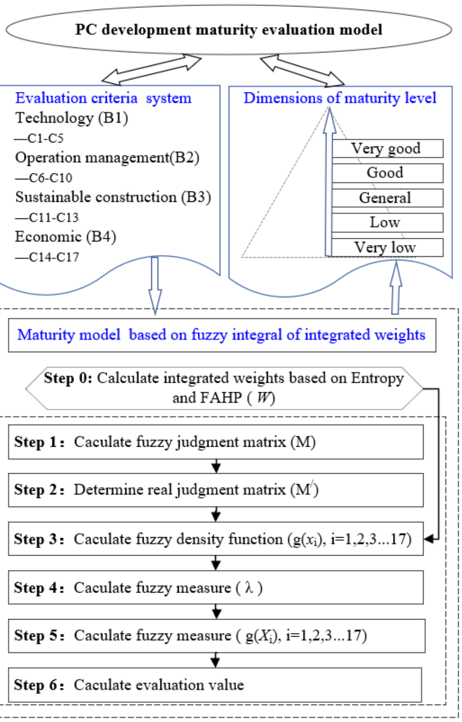

FIGURE 2. Flowchart of the maturity evaluation model.

Moreover, the fuzzy integral based on the AHP-Entropy method has been developed to evaluate the firms' innovation capability [37], [46]. However, there lack of fuzzy integral methods based on FAHP-Entropy, which can be more accurate and practical. Thus, this study aims to provide a fuzzy integral model based on FAHP-Entropy for evaluating the maturity of PC development.

III. RESEARCH METHODOLOGY

The PC development maturity model based on fuzzy integral is depicted in Figure 2. The model can be separated into four main parts: (5) identification of evaluation criteria system (e.g., technology, management, sustainability, or economy and society); (6) the determination of maturity level (e.g., very low, low, general, good, and very good); (3) the calculation of the criteria' weights using FAHP-Entropy method; (4) the calculation of maturity level using fuzzy integral. An outline of the model is shown in Figure 2.

A. CRITERIA SYSTEMS

In this study, the criteria for evaluating PC development maturity for construction firms were determined through the literature review and in-depth interviews.

A systematic literature review was first undertaken to identify initial evaluation criteria. Specifically, we searched journal articles in Scopus and Web of Science using keywords such as prefabricated construction, prefabrication development, maturity evaluation, and so on. As a result, we concluded that properties of prefabricated product, performance of prefabricated projects, managerial improvement, and

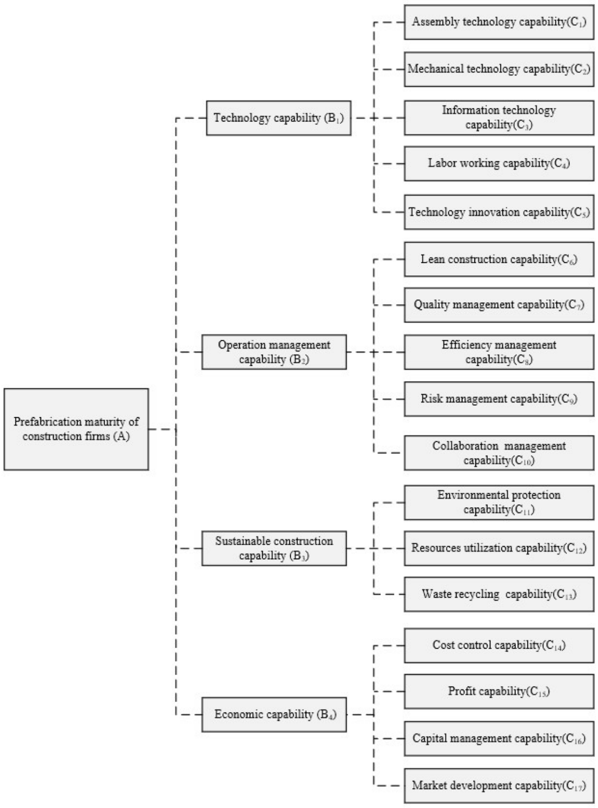

FIGURE 3. **The evaluation system of the criteria.**

technical innovation were the main research areas from the perspective of construction firms [10]. Furthermore, these are critical indicators for evaluating development maturity for construction firms, and should be used to identify the evaluation criteria [47].

In-depth interviews with ten experts (one government officer, two developers, five contractors, and two consultants) were then conducted to validate the rationality and comprehensiveness of the initial criteria. These experts were mainly PC stakeholders with at least five years of experience in PC. Based on their practical experiences, they evaluated each criteria and provided suggestions on whether certain initial criteria should be adjusted, added, or deleted.

Based on these, technology capability, operation management capability, sustainable construction capability, and economic capability turn to be the four main criteria for the maturity model. These main criteria consist of a series of specific sub-criteria (Figure 3).

Technology capability is foundational to PC development, which is considered to be the main constraint on the original stage of development in China. This capability includes construction technology in assembling and mechanics [48], information technology [10], [49], labor working [50], and technology innovation [7], [48].

Operation management capability is a critical to improve PC development maturity, since PC processes are industrialised, and should be controlled organically through configuring operation resources [51], [52]. This capability includes lean construction [10], [53], the management and control of quality [54], efficiency [5], [50], risk management [10], [55], and collaboration management [7].

Sustainable construction was the most frequently mentioned keyword in PC research. Furthermore, the PC impact on sustainability has been widely explored [9], [10]. Sustainable construction capability is thus a critical reflection of PC maturity. Generally, this capability could be reflected in environment protection [56], resource utilisation [57], and waste recycling [58].

Economic capability is the main consideration for stakeholders. It has been considered as one of the major hindrances to PC acceptance, due to PC's higher initial cost and lower profit [7], [59]. In theory, PC projects can cost less than traditional construction based ones when extra costs are better controlled (e.g., skilled labor training, initial investment, and logistic fee) [48]. This capability involves four indicators, namely, cost control [5], [48], profit [60], capital management [61], and market development [60].

B. DIMENSIONS OF PREFABRICATION DEVELOPMENT MATURITY

The dimensions of PC development maturity are the reflection of the level of capability. The number of maturity dimensions generally falls between three and six, with five being the most common [18], [32]. PC development maturity is thus taken to have five levels, generally represented as low, relatively low, general, good, and excellent. Moreover, different maturity levels reflect different aspects of capabilities and development of maturity criteria, such as prefabrication technology, management, labor, and R&D [18], [31], [32]. For the ranges of fuzzy integral scores corresponding to the level, these can be described in the type of triangular fuzzy number (TFN) or real number [62]–[64]. Especially, the real number type obtained better adoption in describing the precise capability level of evaluation object in [64]. Our study also uses this type of fuzzy integral scores, since our study focuses on providing valuable information for construction firms to understand their accurate PC development maturity level for making more effective measures of improving maturity. The levels of maturity with the fuzzy integral scores are shown in Table 1.

C. EVALUATING MODEL

The evaluation model for PC development maturity is based on the Choquet fuzzy integral. The evaluation process consists of six steps, which are shown as follows.

Step 1: Calculation of criterion weights

A method integrating FAHP and Entropy is used to calculate the criterion weights, W_i. Integrated weights are more accurate and practical, through considering both subjective weights based on FAHP and objective weights based on Entropy [65, 66]. Additionally, they eliminate the difficulty in obtaining practical data and the subjective nature of expert evaluation.

TABLE 1. Description of maturity levels.

Maturity level	Fuzzy integral score	Feature description
Very low	[0,0.3)	A lack of technology, management, and skilled labor relating to PC.
Low	[0.3,0.5)	A preliminary level of PC capability in technology and management. The number of skilled workers and PC works is increasing.
General	[0.5,0.7)	PC market scale is increasing. Not only technology, management, and worker skills , but also R&D and economic capability are developed.
Good	[0.7,0.9)	PC capability of all aspects is high. In particular, environmental capability rapidly increases.
Very good	[0.9,1.0]	PC capability meets the requirements of the PC industry. The core competence becomes higher.

Step 1.1: Objective weights based on the entropy method

The entropy method is commonly used to calculate objective weights, relying on practical values of criteria [32]. Entropy relates to the fact that, the more various the values of a factor for different construction firms, the larger the weight of the factor [32, 67, 68]. The calculation processes of objective weights using Entropy are illustrated as follows.

(5) The data collection

There are two types of data should be collected, namely, the criteria value evaluated by experts and the maximum and minimum value of the criterion. These values are linguistic terms, including extremely poor (EP), very poor (VP), poor (P), a little poor (LP), common (C), a little good (LG), good (G), very good (VG), and extremely good (EG). Furthermore, they should be transformed into intuitive fuzzy numbers (IFN), according to [69].

(6) The integrated IFN criteria values

Because the subjective IFN criteria values for any evaluation object are evaluated by E experts, these values are should be integrated into one comprehensive IFN value based on expert weights.

Taking E to be the number of experts, and $\mathrm{B_e}(\pi)$ as the trust function for expert e, the weight of expert e is λ_e, where $i = 1, 2, 3, \ldots s$. Furthermore, $\mathrm{B_e}(\pi)$ and λ_e can be calculated by the following equations.

$$B_e(\pi) = -1/(\sum_{i=1}^{s} \sum_{j=1}^{r} \pi_{ij}^{e}) ln(\sum_{i=1}^{s} \sum_{j=1}^{r} \pi_{ij}^{e}) \tag{1}$$

$$\lambda_e = B_e(\pi) / \sum_{e=1}^{E} B_e(\pi) \tag{2}$$

Then, the integrated IFN criteria value x_{ij}^{*} corresponding to $x_{ij} = (\mu_{ij}^{e}, \gamma_{ij}^{e}, \pi_{ij}^{e})$ can be determined:

$$\begin{aligned} x_{ij}^{*} &= (x_{ij}^{1})^{\lambda_1} \otimes (x_{ij}^{2})^{\lambda_2} \ldots \oplus (x_{ij}^{e})^{\lambda_e} \oplus \ldots \oplus (x_{ij}^{E})^{\lambda_E} \\ &= (\prod_{e=1}^{E} (\mu_{ij}^{e})^{\lambda_e}, 1 - \prod_{e=1}^{E} (\gamma_{ij}^{e})^{\lambda_e}, \\ &\quad \prod_{e=1}^{E} (\gamma_{ij}^{e})^{\lambda_e} - \prod_{e=1}^{E} (\mu_{ij}^{e})^{\lambda_e}) \end{aligned} \tag{3}$$

(3) The calculation of criteria's weights

$\omega = (\omega_1 \omega_{2,} \omega_{i,} \ldots \omega_s)$ are the objective criterion weights. Specially, ω_i is the objective weight of criterion i and $\omega_i \geq 0, i = 1, 2, \ldots s \sum_{i=1}^{s} \omega_i = 1$.

The mean value of criterion i can thus be calculated using the equation:

$$\begin{aligned} \overline{x}_{ij} &= (x_{i1} \oplus x_{i2} \oplus \ldots \oplus x_{ij} \oplus \ldots \oplus x_{ir})/r \\ &= (\prod_{j=1}^{r} (\mu_{ij})^{\frac{1}{r}}, 1 - \prod_{j=1}^{r} (1 - \gamma_{ij})^{\frac{1}{r}}, \\ &\quad \prod_{j=1}^{r} (1 - \gamma_{ij})^{\frac{1}{r}} - \prod_{j=1}^{r} (\mu_{ij})^{\frac{1}{r}}) \end{aligned} \tag{4}$$

Then, the entropy value σ_i of criterion i can be calculated as:

$$\sigma_i = -1/ln(r) \sum_{j=1}^{r} [\frac{d(x_{ij}, \overline{x}_{ij})}{\sum_{j=1}^{r} d(x_{ij}, \overline{x}_{ij})} ln(\frac{d(x_{ij}, \overline{x}_{ij})}{\sum_{j=1}^{r} d(x_{ij}, \overline{x}_{ij})})] \tag{5}$$

Here, d is the distance between x_{ij} and $\overline{x}_{ij}$, given in the next equations.

d can be calculated using equation (6), from $x_{ij} = (\mu_{ij}, \gamma_{ij}, \pi_{ij}), \overline{x}_{ij} = (\overline{\mu}_{ij}, \overline{\gamma}_{ij}, \overline{\pi}_{ij})$.

$$d(x_{ij}, \overline{x}_{ij}) = \sqrt{\frac{1}{2} \{(\mu_{ij} - \overline{\mu}_{ij})^2 + (\gamma_{ij}^{e} - \overline{\gamma}_{ij})^2 + (\pi_{ij} - \overline{\pi}_{ij})^2\}} \tag{6}$$

Ultimately, the ω_i can be calculated using:

$$\omega_i = \frac{1 - \sigma_i}{\sum_{i=1}^{s} (1 - \sigma_i)} \tag{7}$$

Step 1.2: The objective weights based on FAHP

FAHP is widely used to calculate subjective weights based on experts' opinions. The calculation processes of FAHP mainly consist of four steps [70]: (1) constructing pairwise comparison matrixes by integrating experts' evaluation of each factor with the geometric mean method (GMM); (2) determining fuzzy weights; (3) converting the fuzzy weights into real weights with defuzzification; (4) determining the final weights through normalizing.

(1) The construction of fuzzy pairwise comparison matrixes

Constructing a fuzzy pairwise comparison matrix based on the relative importance scores among the criteria collected from experts is an important process for calculating subjective weights based on FAHP. The relative importance scores are evaluated by experts with the triangular fuzzy number (TFN). TFN was indicated by (l, m, u), where m value was determined using a 1 to 9 scale[66], [71], l and u were calculated according to [72].

The calculating processes of FAHP are illustrated as here using one criteria as an example. The value f represents the number of main criteria (B_c). n is the number of sub-criteria (C_i) corresponding to a certain main criteria, where $n = 1, 2, 3, \ldots, s$.

First, the fuzzy judgment matrix A_c^* can be constructed as follows.

$$A_c^* = \begin{bmatrix} (1,1,1) & a_{12}^* & \dots & a_{1n}^* \\ a_{21}^* & (1,1,1) & \dots & a_{2n}^* \\ \dots & \dots & \dots & \dots \\ a_{n1}^* & a_{n2}^* & \dots & (1,1,1) \end{bmatrix} \tag{8}$$

In this matrix, a_{ij}^* is the mean value of the C_i sub-criteria's relative importance scores corresponding to the c main criteria from all experts, where $i, j = 1, 2, 3, \dots n$ and $c = 1, 2, 3, \dots f$. The a_{ij}^t are values for the C_i sub-criteria corresponding to the c-th main criteria from the t-th expert, where $t = 1, 2, 3, \dots P$. Moreover, a_{ij}^* can be calculated using the equation (9).

$$a_{ij}^* = \frac{1}{P}(a_{ij}^1 + a_{ij}^2 + \dots + a_{ij}^P) \tag{9}$$

The original fuzzy weight (C_i^c) of the i-th sub-criteria corresponding to the c-th main criteria can then be calculated by equation (10).

$$C_i^c = \sum_{j=1}^{n} a_{ij} / \left(\sum_{i=1}^{n} \sum_{j=1}^{n} a_{ij} \right) \tag{10}$$

Based on this, the fuzzy weights (C^c) of all the sub-criteria corresponding to the main criteria can be calculated. Moreover, the fuzzy weights (S) of all the main criteria corresponding to the evaluation goal can be calculated.

Then, C^c and S should undergo defuzzification, using the equations below. C^c is in this way transformed into the actual weights $d(C^i)$, and S is transformed to $d(S^i)$.

The probability formula equation is used. With the assumption of $C_i = (l_i, m_i, u_i)$ and $C_{i+1} = (l_{i+1}, m_{i+1}, u_{i+1})$, the probability of $C_i \geq C_{i+1}$ can be defined as follows:

$$V(C_i \geq C_{i+1}) = \sup_{x \geq y}[\min(C_i(x)), C_{i+1}(y)] \tag{11}$$

This can be further illustrated as the following.

$$V(C_i \geq C_{i+1}) = \mu(d) = \begin{cases} 1 & m_i \geq m_{i+1} \\ \frac{l_{i+1} - u_i}{(m_i - u_i) - (m_{i+1} - u_{i+1})} & m_i \leq m_{i+1}\ , u_i \geq l_{i+1} \\ 0 & otherwise \end{cases} \tag{12}$$

Therefore, the probability of $C_i > C_{i+1}$ can be considered as the final weight, which is $d(C)$.

$$d(C) = V(C \geq C_1, C_2, C_3 \dots\dots C_i) = \min V(C \geq C_i) \tag{13}$$

Furthermore, $d(C^i)$ and $d(S^i)$ should be normalized using the min–max equation [73], which can be defined in $D(C^i)$ and $D(S^i)$.

Finally, the actual weights of all the criteria corresponding to the research goal can be calculated as equation (14).

$$\theta = (\theta_1, \theta_2, \theta_3, \dots, \theta_s) = D\left(C^i\right) \otimes D\left(S^i\right) \tag{14}$$

Step 1.3: The calculation of integrated weights

The integrated weights can be calculated by combining the objective and subjective weights. Equation (15) can be used to calculate the integrated weights [69].

$$W_i = \eta\theta_i + (1 - \eta)\omega_i \tag{15}$$

In this equation, η was the risk preference factor, which indicates risk neutrality in the experts' evaluation. Generally, η was taken as 0.5.

Step2: The realization of fuzzy judgment matrix M

In the calculating process using the fuzzy integral, the fuzzy judgment matrix containing the criteria values should be real-valued matrix. Thus, the integrated IFN criteria values in step 1.1 should be transformed to real values. If x_{ij}^* is an integrated IFN criteria value, then this is done as:

$$y_{ij} = \mu_{ij} + \frac{\mu_{ij}}{\mu_{ij}j + \gamma_{ij}}\pi_{ij} \tag{16}$$

The fuzzy judgment matrix can thus be described as $M' = (y_{ij})_{sr}, y_i^{max}, y_i^{min}$, which can ultimately be represented by $Y = (Y_{ij})_{sr}$.

Step 3: The calculation of fuzzy density function $g(x_i)$

The integrated weights W_i of the criteria are equal to $g(x_i)$, which can be illustrated as $g(x_i) = W_i$, and $i = 1, 2, 3, \dots$,s [32], [69].

Step 4: The calculation of fuzzy measure λ

Based on $g(x_i)$, the fuzzy measure λ can be calculated using equation (17).

$$\lambda + 1 = \prod\nolimits_{j=1}^{n} (1 + \lambda g(x_i)) \tag{17}$$

Step 5: The calculation of fuzzy measure $g_\lambda(X_i)$

In the fuzzy integral method, normalized values of the criteria are ranked from large to small, which can be reflected as $Y_i \geq Y_{i-1}$. Furthermore, the criteria are renumbered with X_i, and $i = 1, 2, 3, \dots$ s. The calculation equation of $g_\lambda(X_i)$ is shown as follows:

$$g_\lambda(X_i) = \frac{1}{\lambda}[\prod\nolimits_{i=1}^{q} (1 + \lambda g(x_i)) - 1] \tag{18}$$

This means that $g_\lambda(X_1) = g_\lambda(\{x_1\}; g_\lambda(X_2) = g_\lambda(\{x_1, x_2\}; \dots g_\lambda(X_s) = g_\lambda(\{x_1, x_2, \dots x_s\})$.

Step 6: Calculation of the evaluation value

The evaluation value can be calculated by Choquet integral, as illustrated in equation (19).

$$\int f dg_\lambda = f(Y_s)\, g_\lambda(X_s) + [f(Y_{s-1}) - f(Y_s)]g_\lambda(X_{s-1}) + \dots + [f(Y_1) - f(Y_2))]g_\lambda(X_1) \tag{19}$$

With $g_\lambda(X_s) = 1$, this equation can be updated to equation (20), shown as follows.

$$\int f dg_\lambda = f(Y_s) + [f(Y_{s-1}) - f(Y_s)]g_\lambda(X_{s-1}) + \dots + [f(x_1) - f(x_2))]g_\lambda(X_1) \tag{20}$$

TABLE 2. Final judgment matrix.

	G_1	G_2	G_3
C_1	(0.602, 0.297, 0.101)	(0.653, 0.246, 0.101)	(0.377, 0.520, 0.103)
C_2	(0.653, 0.246, 0.101)	(0.635, 0.265, 0.101)	(0.377, 0.520, 0.103)
C_3	(0.517, 0.381, 0.102)	(0.585, 0.314, 0.101)	(0.328, 0.569, 0.103)
C_4	(0.517, 0.381, 0.102)	(0.602, 0.297, 0.101)	(0.377, 0.520, 0.103)
C_5	(0.488, 0.404, 0.108)	(0.608, 0.288, 0.104)	(0.241, 0.671, 0.088)
C_6	(0.377, 0.520, 0.103)	(0.409, 0.485, 0.105)	(0.296, 0.615, 0.089)
C_7	(0.688, 0.211, 0.100)	(0.672, 0.227, 0.101)	(0.542, 0.357, 0.101)
C_8	(0.617, 0.283, 0.100)	(0.457, 0.441, 0.102)	(0.433, 0.465, 0.101)
C_9	(0.653, 0.246, 0.101)	(0.635, 0.265, 0.101)	(0.470, 0.426, 0.103)
C_{10}	(0.502, 0.389, 0.109)	(0.488, 0.404, 0.108)	(0.409, 0.485, 0.105)
C_{11}	(0.532, 0.365, 0.103)	(0.398, 0.498, 0.104)	(0.329, 0.569, 0.103)
C_{12}	(0.532, 0.365, 0.103)	(0.491, 0.408, 0.102)	(0.377, 0.520, 0.103)
C_{13}	(0.459, 0.437, 0.105)	(0.522, 0.373, 0.105)	(0.427, 0.468, 0.105)
C_{14}	(0.450, 0.444, 0.106)	(0.495, 0.400, 0.104)	(0.351, 0.547, 0.102)
C_{15}	(0.483, 0.411, 0.106)	(0.483, 0.411, 0.106)	(0.351, 0.547, 0.102)
C_{16}	(0.539, 0.353, 0.108)	(0.708, 0.192, 0.100)	(0.505, 0.393, 0.102)
C_{17}	(0.688, 0.211, 0.100)	(0.555, 0.344, 0.101)	(0.372, 0.523, 0.106)

IV. CASE STUDY

A. DATA COLLECTION

Given the difference in PC experiences, scales, and properties of construction firms, the maturity level and influencing factors for construction firms might be different. Thus, three different types of construction firms were selected as study cases, in order to get a balanced view and verification of the maturity model. Three construction firms which the authors had collaboration within projects were coded by G_1, G_2, and G_3. G_1 was a large nation-owned construction firm; G_2 is a large private construction firm that implements early PC projects; and G_3 is a small construction firm, which has embarked on prefabrication in recent years.

Then, five teams were further constructed to evaluate the three cases-oriented sub-criteria' and FAHP-related TFN values in the aforementioned model. These evaluation teams consisted of different professional agencies, namely, Tianjin University, China State Construction Engineering Corporation, and China Communications Construction Company. The five teams were represented as D_1, D_2, D_3, D_4, and D_5. They were asked not only to evaluate the linguistic value of the sub-criteria for G_1, G_2, and G_3, but also to give TFN importance scores for the FAHP-based calculation.

B. CALCULATION OF INTEGRATED WEIGHTS

1) OBJECTIVE WEIGHTS BASED ON THE ENTROPY METHOD

The linguistic values of all the sub-criteria should first be transformed to IFNs [32], [69]. Then, the expert weights could be calculated using equations (1) and (2) to be $\lambda_1 = 0.200$, $\lambda_2 = 0.199$, $\lambda_3 = 0.199$, $\lambda_4 = 0.200$ and $\lambda_5 = 0.199$. Based on this, the subjective sub-criteria values for G1, G2, and G3 were then integrated into one comprehensive judgment value using equation (3); see Table 2.

The mean score of the comprehensive values $\bar{x}_i$, and the entropy value σ_i could be calculated based on equations (4)–(6). The objective weights ω_i were ultimately calculated with the equation (7), shown below.

$$\omega = (0.075, 0.080, 0.066, 0.060, 0.074, 0.046, 0.055, 0.058, 0.059, 0.046, 0.056, 0.050, 0.046, 0.049, 0.049, 0.063, 0.068).$$

TABLE 3. The weights of B→A.

B→A	Fuzzy weights	Real weights	Normalization	D(S)
B1	(0.154,0.247,0.432)	0.835	0.255	0.255
B2	(0.181,0.297,0.465)	1.000	0.305	0.305
B3	(0.148,0.228,0.349)	0.711	0.217	0.217
B4	(0.136,0.228,0.371)	0.734	0.224	0.224

2) SUBJECTIVE WEIGHTS BASED ON FAHP

The importance scores among all the criteria were determined in TFNs by the five expert teams to construct a fuzzy pairwise comparison matrix. Then, the fuzzy weights S of all the main criteria corresponding to the evaluation goal were selected as an example to illustrate the specific calculation processes. The weights D(S) of B→A were calculated by equations (8)–(13) based on the average value of five expert teams (see Table 3).

Similarly, the weights D(C) of all the sub-criteria corresponding to the main criteria were calculated using the same process. The specific values of D(C) were shown as below.

$$\mathrm{D}(C) = (0.197, 0.197, 0.166, 0.201, 0.239, 0.166, 0.360, 0.147, 0.147, 0.179, 0.316, 0.400, 0.284, 0.295, 0.295, 0.192, 0.217).$$

Then, the weights θ of all the sub-criteria corresponding to the evaluation goal were calculated with equation (14). The specific values of subjective weights θ were shown as below.

$$\theta = (0.050, 0.050, 0.042, 0.051, 0.061, 0.051, 0.110, 0.045, 0.045, 0.055, 0.068, 0.087, 0.062, 0.066, 0.066, 0.043, 0.049)$$

3) INTEGRATED WEIGHTS

The integrated weights W for all the sub-criteria were finally calculated based on the objective weights ω and the subjective weights θ, following equation (15).

$$W = (0.063, 0.065, 0.054, 0.056, 0.067, 0.049, 0.083, 0.052, 0.052, 0.050, 0.062, 0.068, 0.054, 0.057, 0.058, 0.053, 0.058)$$

C. EVALUATING MATURITY USING THE FUZZY INTEGRAL

(1) The normalization of comprehensive judgment value

According to the principles of fuzzy integral, the fuzzy judgment matrix should be transformed into the real judgment matrix $\mathrm{M}' = (\mathrm{y_{ij}})_{sr}$, using equation (16). The maximum and minimum sub-criteria values could also be transformed into real numbers y_i^{max}, y_i^{min}. These real values should then undergo min-max normalization. The final real judgment matrix is illustrated in Table 4.

TABLE 4. Final judgment matrix.

Criteria	Maximum	Minimum	Real values			Normalized values		
			G_1	G_2	G_3	G_1	G_2	G_3
C_1	0.05	0.95	0.670	0.727	0.421	0.689	0.752	0.412
C_2	0.05	0.95	0.726	0.706	0.421	0.752	0.729	0.412
C_3	0.05	0.95	0.576	0.651	0.366	0.584	0.667	0.351
C_4	0.05	0.95	0.576	0.670	0.421	0.584	0.689	0.412
C_5	0.05	0.95	0.547	0.679	0.265	0.552	0.699	0.238
C_6	0.05	0.95	0.421	0.457	0.325	0.412	0.453	0.306
C_7	0.05	0.95	0.765	0.748	0.603	0.794	0.775	0.615
C_8	0.05	0.95	0.686	0.509	0.482	0.706	0.510	0.480
C_9	0.05	0.95	0.726	0.706	0.524	0.752	0.729	0.527
C_{10}	0.05	0.95	0.564	0.547	0.458	0.571	0.552	0.453
C_{11}	0.05	0.95	0.593	0.444	0.366	0.604	0.438	0.351
C_{12}	0.05	0.95	0.593	0.546	0.421	0.603	0.551	0.412
C_{13}	0.05	0.95	0.512	0.583	0.477	0.513	0.592	0.474
C_{14}	0.05	0.95	0.503	0.553	0.391	0.504	0.559	0.379
C_{15}	0.05	0.95	0.540	0.540	0.391	0.545	0.545	0.379
C_{16}	0.05	0.95	0.605	0.787	0.563	0.616	0.819	0.570
C_{17}	0.05	0.95	0.765	0.618	0.416	0.794	0.631	0.406

TABLE 5. Main values for G_1 in the calculation.

original criteria name (C_i)	original criteria value	original criteria ranking (C_i)	ranking criteria name (X_i)	ranking criteria value ($f(X_i)$)	fuzzy density value ($g(x_i)$)	fuzzy measure value ($g(X_i)$)
C_1	0.689	C_7	X_1	0.794	0.083	0.083
C_2	0.752	C_{17}	X_2	0.794	0.058	0.141
C_3	0.584	C_2	X_3	0.752	0.065	0.206
C_4	0.584	C_9	X_4	0.752	0.052	0.258
C_5	0.552	C_8	X_5	0.706	0.052	0.309
C_6	0.412	C_1	X_6	0.689	0.063	0.372
C_7	0.794	C_{16}	X_7	0.616	0.053	0.424
C_8	0.706	C_{11}	X_8	0.604	0.062	0.486
C_9	0.752	C_{12}	X_9	0.603	0.068	0.555
C_{10}	0.571	C_3	X_{10}	0.584	0.054	0.608
C_{11}	0.604	C_4	X_{11}	0.584	0.056	0.664
C_{12}	0.603	C_{10}	X_{12}	0.571	0.05	0.713
C_{13}	0.513	C_5	X_{13}	0.552	0.067	0.780
C_{14}	0.504	C_{15}	X_{14}	0.545	0.058	0.837
C_{15}	0.545	C_{13}	X_{15}	0.513	0.054	0.890
C_{16}	0.616	C_{14}	X_{16}	0.504	0.057	0.947
C_{17}	0.794	C_6	X_{17}	0.412	0.049	0.995

(2) The calculation of fuzzy density function $g(x_i)$ ($i = 1, 2, 3 \ldots 17$)
As in the illustration of the maturity model, the value of $g(x_i)$ was equal to the integrated weights W_i. Therefore, $g(x_i) = W_i$. Then, λ was calculated using equation (17), giving the result -0.01.

(3) The determination of fuzzy measure $g_\lambda(X_i)$
Construction firm G_1 was selected to illustrate the calculated processes of fuzzy measure $g_\lambda(X_i)$, and the final fuzzy evaluation values. The normalized values of the criteria in Table 6 were first ranked from large to small, and the criteria were renumbered with X_i. Then, equation (18) was used to determine the value of $g_\lambda(X_i)$. All the calculated results were shown in Table 5.

(4) The calculation of the evaluation value
Based on all of the above in Table, the evaluation values of final PC development maturity were further determined by equations (19) and (20). The calculated processes were shown below.

$$\int f dg_\lambda = f\,(Y_s) + [f(Y_{s-1}) - f(Y_s)]g_\lambda(X_{s-1}) + \ldots + [f(x_1) - f(x_2))]g_\lambda(X_1) = 0.626$$

The evaluation values for G_2 and G_3 can be calculated in the same way, which were 0.631 and 0.422. Therefore, the final evaluation values of PC development maturity were 0.626, 0.631, and 0.422 for construction firms of G_1, G_2, and G_3, respectively.

V. ANALYSIS AND DISCUSSION

A. ANALYSIS AND DISCUSSION OF DEVELOPMENT MATURITY

As above, the maturity values for G_1, G_2, and G_3 were calculated using the fuzzy integral with the integrated weights of FAHP-Entropy. As illustrated in TABLE 1, there were five maturity levels. To demonstrate the maturity levels of G_1, G_2, and G_3 clearly, the relationships between maturity evaluation

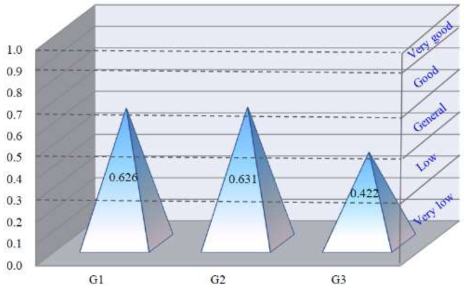

FIGURE 4. Maturity evaluation value of G_1, G_2 and G_3.

values of G_1, G_2, and G_3 and maturity levels were depicted in Figure 4.

As illustrated in Figure 4, the PC development maturity values of G_1, G_2, and G_3 are 0.626, 0.631 and 0.422, which fall into the General, General and Low maturity levels, respectively. Their maturity levels are different, which is in line with the practice.

G_2 and G_1 have a general maturity level, which indicates that their capability is relatively high with the increasing prefabrication market scale. In fact, G_2 and G_1 are large construction firms that have developed PC works involving manufacturing, logistics, and assembly for many years. Furthermore, they have made some achievements in technology and management of PC. For example, G_2 created a kind of facility to reduce deficiencies of PC components while storing and transporting processes. Based on this, they have obtained relatively higher market scales and greater resources, compared with other construction firms.

However, they are very far from a Very Good maturity level. Therefore, they also need to pay more attention to improve their maturity level by undertaking a series of measures related to technology, management, innovation, and so on [10]. In such a context, it should be noted that the construction firms that have obtained a larger PC scale market share in China are located into the general level of PC development maturity. To some extent, this reflects the relatively limited development of the Chinese PC sector [48]. One reason for this is the limited resources that construction firms can obtain during this preliminary stage of development of PC in China [7].

For construction firm G_3, it is located in the low maturity level, indicating that it possesses preliminary capability in the technology and management, and has limited skilled laborers and market scale. In fact, G_3 is a small construction firm that has been developing PC works only since 2016, with the incentives of the Chinese government. There are a series of barriers resulting in its low maturity level, mainly including the large initial investment, the shortage of skilled labor, the lack of technical and management experience, the immature national standards [48], [74]. Thus, to improve the PC development maturity of small construction firms, not only should the firms take effective measures [7], the government should also give them more support and guidelines such as incentives and technology standards [75].

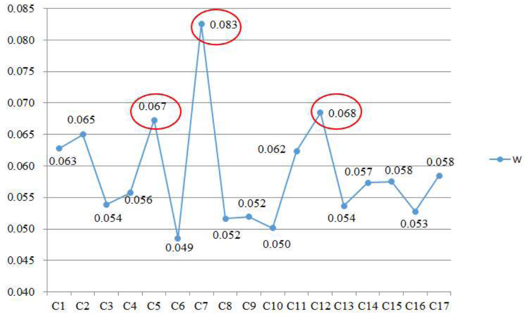

FIGURE 5. Sub-criteria' weights.

B. ANALYSIS AND DISCUSSION OF KEY SUB-CRITERIA BASED ON WEIGHTS

The sub-criteria's weights can be used to identify the critical factors affecting PC development maturity for construction firms during the current development status. Furthermore, the understanding of these critical factors can be used as reference directions for improving their PC development maturity. The weights are depicted in Figure 5, using a line chart.

The top three critical factors based on the weights are C_7, C_{12}, and C_5, marked with red circles, which are quality management capability, resource utilisation capability, and technology innovation capability. In previous research and practices, these aspects were also considered as the key influencing factors in PC development [75], [76].

Quality is the most important aspect, not only for traditional construction, but also for PC. Arguably, it is the primary foundation and advantage of PC [54]. Quality management is thus key to PC development maturity for construction firms, which should be placed in the primary position and to take it seriously [54]. Quality management in PC is more difficult for construction firms, due to the more complicated PC processes, such as production, transportation and assembly. In particular, the quality management capability of construction firms is generally weak, with a lack of technology and management experience in the initial stage of PC in China [54]. In fact, construction firms have encountered some quality risks in PC, which limited their PC development maturity, further hindering PC development in China [61]. Construction firms should therefore pay more attention to enhancing their quality management and reducing quality issues, further improving their PC development maturity.

Resource utilisation is the main indicator of environmental and sustainable performance, which is one of the key considerations for the acceptance of the PC mode [75]. In China in particular, PC has been considered the main way of upgrading the construction sector to sustainable development, being thought to solve severe sustainability problems, such as environmental pollution and resource shortages [77]. Resource utilisation therefore has a great impact on PC development maturity. Specifically, resource utilisation involves decreasing construction waste and energy consumption by increasing the efficiency of resource utilisation [78]. However, the resource utilisation capability of construction firms is relatively limited, because of deficiencies in PC experience, technology, and management. This has resulted in some issues—for example, the rework of PC components usually occurs in the production and assembly processes [79]. Construction firms should thus make effective measures to optimize their resource utilisation capability from various perspectives such as saving energy [57], using green material [80], and decreasing design change and rework [80].

Technology innovation is the key support for the improvement and development of PC, considering the immature technology systems and standards [7]. Technology innovation is thus an important factor relating to the PC development maturity of construction firms. In fact, technology innovation is more challenging for construction firms due to the complex technological system of PC. Particularly in the primary stage of PC in China, construction firms are confronted with a lack of national standards and limited R&D resources. Construction firms are generally weak in PC innovation capability [7]. Due to their limited innovation capability, the existing PC standard and system are immature, which has resulted in some issues further impeding Chinese PC development. Not only is technology innovation attractive to construction firms that have invested in it, but it is also promoted by the Chinese government. This can bring about more advanced standards and craft relating to assembly, mechanical, and information aspects, which are critical to improve PC development maturity, allowing rapid development of PC [7], [48].

In practice, these are critical to the PC development maturity of construction firms, with frequent reorganization among stakeholders. They are thus consistent with the practice, verifying the validity of the maturity evaluation model.

VI. CONCLUSION

Many construction firms have undertaken PC practice under the incentive framework of the Chinese government. However, they have encountered some hindrances in improving PC project performance. To some extent, this is due to the unclear understanding of their PC development maturity and influencing factors.

This study has thus focused on solving this issue by providing a maturity evaluation model using fuzzy integral. Especially, a FAHP-Entropy method was initially explored to weigh evaluation criteria for improving the accuracy of calculating results based on fuzzy integral. Additionally, seventeen evaluation criteria are identified, which are categorised into technology, operational management, sustainable, and economic aspects. This provides a holistic map of factors influencing PC development maturity for construction firms. Furthermore, three critical factors, namely, quality management capability, resource utilisation capability, and technology innovation capability, are

determined and analysed. Construction firms should pay more attention to these factors while making measures of improving their PC development maturity. Moreover, the maturity level of the three study cases is general or low through analysing their maturity evaluation results. The firms should further improve their maturity level according to the identifying factors, especially the critical ones. Overall, the results are in accordance with previous research and practical experience.

Although this study contributes to constructing maturity model that can help construction firms to quantitatively know the maturity level, and the critical influencing factors, it also has some limitations. The first limitation is that, despite the effect of the model has been verified using study cases, we have not compared it with other evaluation methods, such as AHP. The other one refers to the limited number of construction firms and experts that were investigated in our study.

In view of this, our study can be further revolved around comparing with other multi-criteria evaluation methods to optimise the model, conducting more case studies to verify the model and explore the PC sector oriented development maturity and influencing factors, and formulating continuous measures of improving PC development maturity based on the identified factors.

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