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A Novel Risk Assessment Model for Prefabricated Building Construction Based on Combination Weight and Catastrophe Progression Method

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Abstract: To reduce the construction risk of prefabricated building projects, a prefabricated building construction risk assessment index system with five first-level indicators and 21 second-level indicators was established based on human, machine, material, management, and environmental factors. By combining the analytic hierarchy process (AHP), CRiteria Importance through Intercriteria Correlation (CRITIC), and catastrophe theory, a risk assessment model of prefabricated building construction based on a combination weighting and catastrophe progression method was constructed. The effectiveness of the assessment model using the combination weighting and catastrophe progression method was verified through case analysis. The results show the following: (1) The quality of the prefabricated components, the standardization degree of the prefabricated components, and the environment of the installation working space in the construction risk assessment indicators of prefabricated buildings obtained by the AHP-CRITIC weighting method have higher weights. (2) Four prefabricated construction enterprises under China State Construction Corporation are evaluated, and the evaluation results effectively evaluate the project risk situation before an accident occurred, achieving the goal of improving the risk management efficiency. (3) The AHP-CRITIC weighting method can reflect the fuzziness of the construction risk of the evaluated project, effectively reduce information loss, and thus make the evaluation results more accurate. The conclusions have important practical significance for improving the construction risk management of prefabricated buildings.

Keywords: AHP method; catastrophe progression method; construction risks; CRITIC method; prefabricated building

1 INTRODUCTION

Prefabricated building construction began to develop in China in the 1950s. However, due to the limitations of the theory, technology, and industrialization, prefabricated buildings gradually faded out of sight in the middle and late 1980s. In recent years, with the emergence of labor shortages and the demand for low-carbon emissions, energy conservation, and environmental protection, prefabricated buildings have gradually become the focus of attention due to their energy conservation, emission reduction [1], and labor-intensive characteristics [2]. China has made great progress in the standardized design, component decomposition, and construction mechanization, which has also provided a solid foundation for the large-scale development of prefabricated buildings. Since 2016, China has successively issued several policies to promote the development of prefabricated buildings, creating a good environment for the development of these buildings, and has made great achievements in the process of comprehensively promoting prefabricated buildings. However, compared to traditional buildings, the construction process of prefabricated buildings is more complex and requires higher machinery and personnel. The unique work of prefabricated buildings, such as unloading and stacking of prefabricated components, also puts forward higher requirements for on-site construction management. Meanwhile, the use of prefabricated buildings began late in China and lacked professional prefabricated technology and management personnel, leading to construction risk incidents from time to time. Therefore, it is necessary to find an effective risk assessment method for prefabricated buildings, evaluate the risk status of prefabricated building construction projects before accidents occur, and improve the risk management efficiency.

Prefabricated buildings are a kind of building form in which various components that are produced quantitatively in a factory are assembled and connected at the construction site. The emergence of prefabricated buildings has greatly promoted China's construction industrialization and the rapid development of the construction industry [3]. Prefabricated buildings have high assembly efficiencies, low costs, and energy conservation characteristics, and they are gradually being applied and developed all over the country. Use of prefabricated buildings will become a new trend in the construction industry in the next few years. Compared with the traditional pouring construction method, prefabricated buildings are greener, and the construction period is shortened, with huge economic and social benefits [4]. However, due to the short development times of prefabricated buildings in China and the influence of the assembly equipment, technology, and on-site management level, there may be many potential risks in the construction process.

In the context of aggressively promoting the construction of a resource-conserving and environmentally friendly society, prefabricated buildings have become the key to promoting the transformation and upgrading of the construction industry, with their remarkable advantages of energy conservation, consumption reduction, and environmental protection [5]. However, in the hoisting process of prefabricated buildings, the working space is multi-dimensional, the visibility is poor, the risk is high, and construction safety accidents can easily occur. Therefore, it is of great significance to scientifically and reasonably evaluate the construction risks of prefabricated buildings to improve the safety management of prefabricated buildings.

2 STATE OF THE ART

Various scholars have discussed the identification of construction safety risk factors of prefabricated buildings, mainly focusing on traditional safety analysis methods, such as through a literature survey [6], the Delphi method [7], and the chain of events [8]. However, the above methods did not fully consider the accidents caused by the interactions between influencing factors, lacked in-depth analysis of the influencing mechanisms between factors, and also lacked a description of the nonlinear relationships between various influencing factors [9].

The study of the construction risk assessment of prefabricated buildings has increasingly become the focus of scholars. The safety assessment of prefabricated buildings has formed a perfect standard system, which mainly focuses on fuzzy comprehensive assessment [10], the analytic hierarchy process [11], and attribute mathematics [12]. The existing studies have applied grey clustering, cloud models, variable fuzzy sets, and other methods to the field of construction safety assessment of prefabricated buildings [13]. Considering that there are many uncertainties in the construction of prefabricated buildings, the above methods of prefabricated building construction risk assessment cannot deal with uncertainties in the construction process well and have no evident advantages in performing construction safety risk assessment in complex systems [14]. Li et al. [15], based on the analysis of the risks associated with prefabricated buildings, used the fuzzy analytic hierarchy process to evaluate the risks in the construction phase of prefabricated buildings. Wang et al. [16] introduced system dynamics theory to identify the risks and hidden danger factors in the construction phase of prefabricated buildings, established an evaluation model using the Vensim software, and built a risk management mechanism for prefabricated buildings. Wu et al. [17] analyzed the risks in the process of transportation, hoisting, and installation of prefabricated components in the construction of prefabricated buildings, built an evaluation model for prefabricated buildings based on a fuzzy comprehensive evaluation method, and proposed targeted risk prevention measures. Li et al. [18], based on the analysis of prefabricated building engineering practice, designed a construction risk evaluation index system for prefabricated buildings and used a cloud model and Bayesian network to evaluate the construction risks of prefabricated buildings. Clyde et al. [19] established an index system using the grey correlation degree, calculated the index weight using the structural equation model, analyzed the potential influencing factors of the construction safety risk of prefabricated buildings, and finally proposed corresponding countermeasures and suggestions. Muhammad et al. [20] established a comprehensive fuzzy extension evaluation model for the risk of prefabricated buildings using the extension theory and verified the effectiveness of the model in the construction risk evaluation of prefabricated buildings. Shen et al. [21] combined the binomial coefficient method and entropy weight method to establish a matter-element model to evaluate the construction risks of prefabricated buildings. Zhao [22] used document co-citation and bibliographic coupling techniques to conduct a review of global construction risk management, and believed that advanced risk analysis techniques, information and communication technology-driven CRM are receiving increasing attention. Wuni et al. [23] conducted a risk assessment of onsite assembly risk factors for modular integrated construction projects and found top five on site assembly risk factors such as modules installation discrepancies and errors.

The existing construction risk assessment methods for prefabricated buildings have advantages, but there are still certain shortcomings. For example, in the weight calculation process, some weight methods are too complex to calculate and have weak operability [24]. The qualitative or quantitative attributes of the indicators were not considered [18]. Compared with other methods, the catastrophe progression method is suitable for situations with complex factor conditions and a combination of qualitative and quantitative indicators, and it has the advantage of dynamically evaluating the object. Based on this, in this study, the analytic hierarchy process-CRiteria Importance Through Intercriteria Correlation (AHP-CRITIC) weight method was used to rank the importance of indicators in the catastrophe sequence model, and a construction risk assessment model of prefabricated buildings was designed based on the combination weight and catastrophe progression method, which reduced the subjectivity of decision analysis in the risk assessment process. The proposed combination weight and catastrophe progression method considers the dynamic nature of the construction risk assessment of prefabricated buildings, overcomes the limitations of subjective weighting in traditional assessment methods, and improves the accuracy of construction risk assessment of prefabricated buildings.

3 METHODOLOGY

3.1 Catastrophe Progression Method

3.1.1 Catastrophe Model

In the catastrophe progression method, assuming that a certain catastrophe type has a potential function $f(x)$, the solution of $f'(x)=0$ provides the equilibrium surface, and the solution of $f''(x)=0$ provides the singular point set equation of the equilibrium surface. Solving $f'(x)=0$ and $f''(x)=0$ to obtain the bifurcation point set equation is the research core of catastrophe theory. When the control variable satisfies the bifurcation point set equation, the target system will undergo a catastrophe.

(1) Cusp point catastrophe model: The potential function of cusp point catastrophe model is $f(x)=x^4+Bx^2+Cx,$ and thus $f'(x)=0$ is $4x^3+2Bx+C=0$ and $f''(x)=0$ is $12x^2+2B=0.$ Solving $f'(x)=0$ and $f''(x)=0$ yields the bifurcation point set equations $B=-6x^2$ and $C=8x^3$ in the decomposition form of the cusp point catastrophe model, and combining the above two bifurcation point set equations yields the bifurcation equation $8B^3+27C^2=0$ of the cusp point catastrophe model.

Similarly, the bifurcation point set equations of other catastrophe models can be further obtained.

(2) Coattail catastrophe model: The decomposition form $f(x)=x^5+Bx^3+Cx^2+Dx$ yields the bifurcation point set equations $B=-6x^2$, $C=8x^3$, and $D=-3x^4$.

(3) Butterfly catastrophe model: The decomposition form $f(x)=x^6+Bx^5+Cx^3+Dx^2+Ex$ yields the bifurcation point set equations $B=-10x^2$, $C=20x^3$, $D=-15x^4$, and $E=4x^5$.

(4) Wigwam catastrophe model: The decomposition form $f(x)=x^7+Bx^6+Cx^5+Dx^3+Ex^2+Fx$ yields the bifurcation point set equations $B=-x^2$, $C=2x^3$,

$D=-2x^4$, $E=4x^5$, and $F=-5x^6$. The wigwam catastrophe model is not an elementary catastrophe model (with the state dimension of 1 and the control dimension of 5), but it is often used in the catastrophe progression model for evaluation.

3.1.2 Dimensionless Processing of Evaluation Indicators

The evaluation indicators mainly include qualitative and quantitative indicators. The range transformation method is used to perform dimensionless processing on the quantitative indicators. The Delphi method or questionnaire method is used to convert qualitative indicators into quantitative indicators. Based on the different evaluation indicators, quantitative indicators can be divided into positive and negative indicators. The larger a positive indicator value, the better, while the smaller a negative indicator value, the better. The conversion formulas for positive and negative indicators are shown, respectively, as follows:

$$\delta_{ij}^{+}=\frac{x_{ij}-\min x_j}{\max x_j-\min x_j} \tag{1}$$

$$\delta_{ij}^{-}=\frac{\max x_j-x_{ij}}{\max x_j-\min x_j} \tag{2}$$

3.1.3 Normalization Formula for Catastrophe Model

With the cusp point catastrophe model as an example, $x_B=\sqrt{-\frac{B}{6}}$ and $x_C=\sqrt[3]{\frac{C}{8}}$ can be obtained by solving $B=-6x^2$ and $C=8x^3$, where x_B corresponds to the x value of B, and x_C corresponds to the x value of C. To combine with fuzzy mathematics membership functions and ensure the same range of values for the control and state variables, the values of x_B and x_C are limited to [0,1]. Therefore, by letting $B=6B'$ and $C=8C'$, $x_B=\sqrt{B'}$ and $x_C=\sqrt[3]{C'}$ can be obtained. Thus, the values of B', C', and x are limited to [0, 1], achieving the combination of a catastrophe model and fuzzy mathematics. The normalization formulas of the cusp point catastrophe model are $x_B=\sqrt{B}$ and $x_C=\sqrt[3]{C}$. Similarly, the normalization formulas for other catastrophe models can be obtained, as shown in Tab. 1.

Table 1 Normalization formulas for commonly used catastrophe models

Type	Control dimension	Potential function	Normalization formula
Fold catastrophe	1	$f(x)=x^3+Bx$	$x_B=\sqrt{B}$
Cusp point catastrophe	2	$f(x)=x^4+Bx^2+Cx$	$x_B=\sqrt{B}, x_C=\sqrt[3]{C}$
Coattail catastrophe	3	$f(x)=x^5+Bx^3+Cx^2+Dx$	$x_B=\sqrt{B}, x_C=\sqrt[3]{C}, x_D=\sqrt[4]{D}$
Wigwam catastrophe	4	$f(x)=x^6+Bx^5+Cx^3+Dx^2+Ex$	$x_B=\sqrt{B}, x_C=\sqrt[3]{C}, x_D=\sqrt[4]{D}, x_E=\sqrt[5]{E}$
Wigwam catastrophe	5	$f(x)=x^7+Bx^6+Cx^5+Dx^3+Ex^2+Fx$	$x_B=\sqrt{B}, x_C=\sqrt[3]{C}, x_D=\sqrt[4]{D}, x_E=\sqrt[5]{E}, x_F=\sqrt[6]{F}$

3.1.4 Principle of Catastrophe Decision Making

When the catastrophe progression method is used to comprehensively evaluate the construction risk of a prefabricated building, based on the different influence directions of the control variables on the state variables, the catastrophe decision making follows the two principles of complementarity and non-complementarity. The principle of complementarity refers to the complementary effect of the control variables in a system on the state variables. If the value of the intermediate state variable x is the average value of the initial catastrophe sequence of the control variable, then $x=(x_1+x_2+\cdots+x_n)/n, n\le 5$. The principle of non-complementarity refers to the fact that all control variables in the system do not affect the state variable. In this case, if the value of the intermediate state variable x is the minimum value of the state variable, then there exists $x=\min\{x_1, x_2, ..., x_n\}, n\le 5$, where x is the state variable, and x_1, x_2, …, x_n are the catastrophe level values of the control variable.

3.2 Improvement of Catastrophe Progression Method based on Combination Weights

At present, most scholars use the Delphi method or questionnaire method to rank the control variables, but the ranking results are often very subjective and cannot be changed according to the relative degree of change of each control variable, resulting in the lack of objectivity and rationality of the evaluation results. In this study, the AHP-CRITIC combination weight method is used to rank the importance of the evaluation indicators, which ensures the objectivity and rationality of the construction risk evaluation index system of a prefabricated building.

3.2.1 Analytic Hierarchy Process (AHP) Method

In an AHP model, the lowest level is generally the factor layer, and the identified basic risk factors are used as secondary indicators for risk assessment. The middle layer serves as the criterion layer, categorizing risk factors as the primary indicator for risk evaluation. The highest level is the target level, which is the decision-making goal that the risk quantification needs to achieve. After determining the evaluation objectives, plans, standards, and indicators, a systematic hierarchical model can be constructed to comprehensively identify and analyze risk factors. Then, a judgment matrix was established, and based on the established risk hierarchy, factors are compared in pairs. Based on their importance, the relationship between factors was determined using a nine-level scale to obtain the judgment matrix.

The products of the judgment matrix elements a_{ij} were calculated by row, resulting in a new vector $\boldsymbol{M}_i$, defined as follows:

$$\boldsymbol{M}_i = \prod_{j=1}^{n} a_{ij} \, (i, j = 1, 2, 3, ..., n) \tag{3}$$

By computing the n^{th} root of each element of the new vector $\boldsymbol{M}_i$, vector $\boldsymbol{r}_i$ is obtained, defined as follows:

$$\boldsymbol{r}_i = \sqrt[n]{\boldsymbol{M}_i} \tag{4}$$

Subsequently, $\boldsymbol{r}_i$ is normalized to obtain the weight vector $\boldsymbol{W}_i$, largest eigenvalue $\lambda_{\max}$, consistency index T, and consistency ratio Q. The formulas are shown as follows:

$$\boldsymbol{W}_i = \frac{\boldsymbol{r}_i}{\sum_{i=1}^{n} \boldsymbol{r}_i} \tag{5}$$

$$\lambda_{\max} \approx \frac{1}{n} \sum_{i=1}^{n} \frac{\sum_{i=1}^{n} (a_{ij} \boldsymbol{W}_j)}{\boldsymbol{W}_i} \tag{6}$$

$$T = \frac{\lambda_{\max} - n}{n - 1} \tag{7}$$

$$Q = \frac{T}{K} \tag{8}$$

The consistency ratio can be used to determine whether the matrix has passed the consistency test.

3.2.2 Objective Weight Calculation based on Criteria Importance through Intercriteria Correlation (CRITIC) Method

The indicators for evaluating the construction risk of a prefabricated building often have a certain relevance. In this study, the CRITIC method was used to calculate the objective weight. Assuming there are m schemes with n indicators for each scheme, the evaluation matrix $\boldsymbol{X}$ can be represented, and the evaluation schemes for the elements in the matrix are the values associated with the corresponding indicators. The formula is shown as follows:

$$\boldsymbol{X} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2m} \\ \vdots & \vdots & & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nm} \end{bmatrix} \tag{9}$$

The steps for calculating the objective weights of the indicators using the CRITIC method are as follows.

(1) Indicator homogenization processing: When determining risk assessment indicators, there may be some negative indicators, such as the quality of the prefabricated components. The larger the negative indicator value, the lower the risk, while the larger the positive indicator value, the higher the risk. When these two indicators exist simultaneously, it will increase the difficulty of calculation. Therefore, to facilitate the calculation, it is necessary to normalize the indicators, and the conversion formula is as follows:

$$x'_{ij} = \frac{1}{\lambda + \max|X_i| + x_{ij}} \tag{10}$$

where the indicator value is represented by x_{ij}. The indicator value of the isotropic treatment is represented by x'_{ij}. The maximum value of the i^{th} indicator is represented by $\max|X_i|$. The coordination coefficient is represented by λ and is generally set to 0.1. After the above processing, the evaluation matrix $\boldsymbol{X}'$ after normalization can be obtained.

(2) Standardized processing of indicators: Due to the different meanings and units of each indicator in the evaluation matrix $\boldsymbol{X}'$, it is necessary to convert the values of each indicator to the same standard, as follows:

$$x''_{ij} = \frac{x'_{ij} - \min(x'_{ij})}{\max(x'_{ij}) - \min(x'_{ij})} \tag{11}$$

where x''_{ij} is the standardized indicator value.

(3) Objective weight calculation of indicators: Using the standard matrix $\boldsymbol{X}''$, the standard deviation σ_i of each indicator and the correlation coefficient ρ_{ij} between indicators can be obtained. The formulas are as follows:

$$\sigma_i = \sqrt{\frac{1}{m} \sum_{j=1}^{m} (x_j^n - \overline{x}_i^n)^2}, \; i = 1, 2, ..., n \tag{12}$$

$$\rho_{ij} = \text{cov}(X_i^n, X_j^n) / (\sigma_i \sigma_j), \; i = 1, 2, ..., n \tag{13}$$

where the mean of the i^{th} indicator is represented by x''_{ij}. The covariance between the i^{th} and j^{th} indicators is represented by $\text{cov}(X_i^n, X_j^n)$. The amount of information G_i contained in each indicator is shown as follows:

$$G_i = \sigma_i \sum_{j=1}^{n} (1 - \rho_{ij}), \; i = 1, 2, ..., n \tag{14}$$

The larger the value of G_i, the higher the relative importance of the i^{th} indicator, and the greater the amount of information it contains. The objective weight β_i of the i^{th} indicator is calculated based on this value as follows:

$$\beta_i = \frac{G_i}{\sum_{j=1}^{n} G_j} \tag{15}$$

3.2.3 Determination of Combination Weights

By improving the AHP method and CRITIC method, the subjective weight vector α and objective weight vector β are obtained, respectively. The comprehensive weight is composed of these two weights, and the weights of each indicator in the evaluation process can be fully reflected through their complementarity. To make the comprehensive weight ω_i of the indicator as close as possible to α_i and β_i, the principle of minimizing the distinguishing information can be adopted to obtain the comprehensive weight ω_i. The objective function is shown as follows:

$$\begin{cases} \min J(\omega) = \sum_{i=1}^{n} \left(\omega_i \ln \frac{\omega_i}{\alpha_i} + \omega_i \ln \frac{\omega_i}{\beta_i} \right) \\ \text{s.t. } \sum_{i=1}^{n} \omega_i = 1,\ \omega_i \geq 0,\ i = 1, 2, ..., n \end{cases} \tag{16}$$

By solving Eq. (16), the comprehensive weight ω_i can be obtained as follows:

$$\omega_i = \frac{\sqrt{\alpha_i \beta_i}}{\sum_{j=1}^{n} \sqrt{\alpha_i \beta_i}} \tag{17}$$

The comprehensive weight vector $\boldsymbol{\omega}$ is defined as

$$\boldsymbol{\omega} = [\omega_1, \omega_2, ..., \omega_n]^{\mathrm{T}} \tag{18}$$

3.3 Influencing Factors of Construction Risk of Prefabricated Buildings

3.3.1 Identification of Evaluation Indicators

To make the established evaluation index system suitable for the characteristics of prefabricated building construction, first, the reports of several construction accidents of prefabricated construction were examined, the causes of the accidents were analyzed, and 26 indices, including the fatigue operation of assembly operators, were extracted. Second, through the analysis of existing studies, 21 evaluation indicators were further determined, including the establishment of a prefabricated construction management system [24, 25]. Finally, based on expert experience, referring to national technical specifications such as the Evaluation Standard for Prefabricated Buildings and the Construction Safety Inspection Standard, five additional evaluation indicators, including the standard degree of prefabricated components, were selected. Through the above three steps, 52 evaluation indicators were preliminarily determined.

The risk indicators of prefabricated building construction were further optimized through a questionnaire survey method, and the questions in the questionnaire were quantified using the Likert-5 scale. The respondents were asked to score the impacts of the indicators on prefabricated building construction and screen out unqualified indicators.

Between October and December 2022, a questionnaire survey was conducted twice on 10 prefabricated construction sites in Zhengzhou, Kaifeng, and Shangqiu, Henan in China. In the first survey, construction workers and construction site management personnel were invited to fill out survey questionnaires. In total, 200 questionnaires were distributed and 180 were collected. After excluding invalid questionnaires, there were still 176 valid questionnaires, with an effective recovery rate of 90%. To verify the reliability of the first survey results, a total of 50 construction industry experts from construction units, owner units, supervision units, design units, and universities were invited for the second rating. By comparison, the difference between the two survey results was about 2%, which had no impact on the indicator screening. Therefore, the evaluation scores of 50 experts were obtained during the second questionnaire survey. A total of 50 questionnaires were collected. After removing invalid questionnaires, there were still 48 valid questionnaires left, with an effective recovery rate of 96%. Results of the reliability and validity analysis of the survey are shown in Tabs. 2 and 3.

Table 2 Reliability statistics

Cronbach's alpha	Number of items
0.952	52

Table 3 Results of Kaiser-Meyer-Olkin (KMO) and Bartlett sphericity test

KMO		0.815
Bartlett Sphericity Test	Approximate chi-squared	2311.202
	Degrees of freedom	936
	Significance	< 0.001

The results indicate that the survey results were reliable and could meet the research objectives.

Table 4 The construction risk assessment index system of prefabricated building

Target layer	First-level indicators	Symbol	Second-level indicators	Symbol
Construction risk of prefabricated building	Personnel risk	*A*1	Level of operational standards for installation personnel	A11
			Risk identification ability of installation personnel	A12
			Installation personnel's sense of responsibility	A13
			Level of operational standards for lifting personnel	A14
	Management risk	*A*2	Construction process management level	A21
			Implementation of construction management system	A22
			Logistics management level of prefabricated components	A23
			Quality inspection of prefabricated components entering site	A24
			Management level of project site	A25
	Material risk	*A*3	Quality of prefabricated components	A31
			Standardization level of prefabricated components	A32
			Dimensions of prefabricated components	A33
	Machine risk	*A*4	Service life of machine	A41
			Maintenance and upkeep of machine	A42
			Selection of transportation and lifting equipment	A43
Construction risk of prefabricated building	Machine risk	*A*4	Safety status of lifting equipment	A44
			Carrying capacity of lifting equipment	A44
	Environmental risk	*A*5	Space environment for installation work	A51
			Standardization level of construction	A52
			Selection of lifting points for prefabricated components	A53
			Impact of construction on environment	A54

To better observe the importance of each indicator and improve the accuracy of the evaluation, further screening was conducted on existing indicators. An average score of 3.8 for each indicator was used in the screening criteria in this study, and ultimately, 21 indicators were retained. The construction risk assessment index system of prefabricated buildings is shown in Tab. 4.

4 RESULTS ANALYSIS AND DISCUSSION

In this study, four assembly construction enterprises (hereinafter referred to as X Branch, Y Branch, Z Branch, and W Branch) affiliated with China State Construction Engineering Corporation Limited were selected as the research objects, and the construction risks of prefabricated buildings were evaluated. Values 1, 3, 5, 7, and 9 represent the degrees of risk control in various situations, with higher scores indicating better risk control.

4.1 Determination of Weights for Indicators at all Levels

Based on previous studies and the construction risks of prefabricated buildings, five secondary indicators were determined in this study, namely the personnel risk, management risk, material risk, machine risk, and environmental risk, and selected 21 related tertiary indicators were then determined to establish a three-tier indicator system. This study used the AHP-CRITIC method to determine the weights of each indicator and calculated the weight values of each three-level indicator. The results are shown in Tab. 5.

Table 5 Calculation results of analytic hierarchy process-CRiteria Importance through Intercriteria Correlation (AHP-CRITIC) method

Target layer	First-level indicators	Second-level indicators	Symbol	AHP weight	CRITIC weight	Combination weight	Rank
Construction risk of prefabricated building	Personnel risk	Level of operational standards for installation personnel	*A*11	0.017	0.024	0.022	17
		Risk identification ability of installation personnel	*A*12	0.051	0.062	0.060	5
		Installation personnel's sense of responsibility	*A*13	0.025	0.030	0.030	12
		Level of operational standards for lifting personnel	*A*14	0.025	0.020	0.024	16
	Management risk	Construction process management level	*A*21	0.033	0.054	0.045	11
		Implementation of construction management system	*A*22	0.034	0.061	0.049	9
		Logistics management level of prefabricated components	*A*23	0.018	0.040	0.029	14
		Quality inspection of prefabricated components entering site	*A*24	0.032	0.069	0.050	8
		Management level of project site	*A*25	0.006	0.051	0.018	18
	Material risk	Quality of prefabricated components	*A*31	0.089	0.080	0.091	1
		Standardization level of prefabricated components	*A*32	0.111	0.047	0.078	3
		Dimensions of prefabricated components	*A*33	0.075	0.034	0.054	7
	Machine risk	Service life of machine	*A*41	0.106	0.034	0.065	4
		Maintenance and upkeep of machine	*A*42	0.032	0.024	0.030	13
		Selection of transportation and lifting equipment	*A*43	0.015	0.046	0.028	15
		Safety status of lifting equipment	*A*44	0.086	0.036	0.059	6
		Carrying capacity of lifting equipment	*A*44	0.030	0.069	0.049	10
	Environmental risk	Space environment for installation work	*A*51	0.079	0.081	0.086	2
		Standardization level of construction	*A*52	0.028	0.047	0.039	17
		Selection of lifting points for prefabricated components	*A*53	0.062	0.012	0.030	5
		Impact of construction on environment	*A*54	0.046	0.077	0.064	12

Table 6 Indicator weights and types of catastrophe systems

Target layer	Catastrophe type	First-level indicators	Combination weight	Catastrophe type	Second-level indicators	Combination weight
Construction risk of prefabricated building	Wigwam catastrophe	Personnel risk	0.118	Butterfly catastrophe	Level of operational standards for installation personnel	0.022
					Risk identification ability of installation personnel	0.060
					Installation personnel's sense of responsibility	0.030
					Level of operational standards for lifting personnel	0.024
		Management risk	0.122	Wigwam catastrophe	Construction process management level	0.045
					Implementation of construction management system	0.049
					Logistics management level of prefabricated components	0.029
					Quality inspection of prefabricated components entering site	0.050
					Management level of project site	0.018
Construction risk of prefabricated building	Wigwam catastrophe	Material risk	0.275	Coattail catastrophe	Quality of prefabricated components	0.091
					Standardization level of prefabricated components	0.078
					Dimensions of prefabricated components	0.054
		Machine risk	0.270	Wigwam catastrophe	Service life of machine	0.065
					Maintenance and upkeep of machine	0.030
					Selection of transportation and lifting equipment	0.028
					Safety status of lifting equipment	0.059
					Carrying capacity of lifting equipment	0.049
		Environment al risk	0.215	Butterfly catastrophe	Space environment for installation work	0.086
					Standardization level of construction	0.039
					Selection of lifting points for prefabricated components	0.030
					Impact of construction on environment	0.064

4.2 Determination of Type of Catastrophe System

According to the catastrophe progression method, the types of catastrophe systems were classified, and the catastrophe system types for each level of the indicators were determined in the evaluation index system. The types of catastrophe systems corresponding to the indicator system are shown in Tab. 6.

4.3 Evaluation Using Catastrophe Progression Method

(1) Criteria and values for index evaluation: According to the requirements of the evaluation objectives, 15 experts in the field of prefabricated buildings were selected in this study. Experts scored the construction risks of prefabricated buildings according to the evaluation criteria. The evaluation criteria and values of the indicators are shown in Tab. 7. The evaluation standard with a low risk is the optimal state, which meets the requirements of 90% of the evaluation criteria. The evaluation standard with a lower risk meets the requirements of 70% of the evaluation criteria. The evaluation standard with a moderate risk meets the requirements of 50% of the evaluation criteria. The evaluation standard with a high risk meets the requirement of 30% of the evaluation criteria. The evaluation standard with an extremely high risk is the worst case, completely failing to meet the predetermined requirements.

Table 7 Criteria and values for index evaluation

Evaluation level	Best	Good	Moderate	Bad	Worse
Evaluation criteria	very low risk	low risk	moderate risk	high risk	extremely high risk
Value	9	7	5	3	1
Value range	[9, 10)	[7, 9)	[5, 7)	[3, 5)	[1, 3)

(2) Dimensionalization of indicators: The average of the expert rating data for each indicator was obtained. Eq. (1) was used for dimensionless processing of the positive indicators, while Eq. (2) was used for dimensionless processing of the negative indicators. In Tab. 8, (+) indicates that the next-level indicator follows the complementary principle, and (−) indicates that the lower-level indicators follow the non-complementary principle.

Table 8 Index evaluation scores and dimensionless values

Target layer	First level	Second level	Average expert rating				Dimensionless value			
			X Branch	*Y* Branch	*Z* Branch	*W* Branch	*X* Branch	*Y* Branch	*Z* Branch	*W* Branch
Construction risk of prefabricated building	A1+	A11	7.24	5.5	5.97	7.22	0.12	0.25	0.485	0.11
		A12	8.8	7.12	8.99	7.9	0	0.06	0.995	0.45
		A13	8.46	5.58	5.6	6.18	0.73	0.29	0.3	0.59
		A14	8.65	8.71	6.18	7.52	0.825	0.855	0.59	0.26
	A2+	A21	7.81	5.79	8.57	8.78	0.405	0.395	0.785	0.89
		A22	5.63	5.93	5.62	6.87	0.315	0.465	0.31	0.935
		A23	5.27	5.48	7.72	5.02	0.135	0.24	0.36	0.01
		A24	7.18	7.56	6.94	7.6	0.09	0.28	0.47	0.3
		A25	6.45	7.78	6.45	6.53	0.725	1.39	0.725	0.765
	A3−	A31	5.77	8.71	6.26	6.11	0.385	0.855	0.63	0.555
		A32	8.37	6.12	6.24	5	0.685	0.56	0.62	0
		A33	8.73	8.76	7.22	6.88	0.865	0.88	0.11	0.94
	A4+	A41	8.52	7.46	6.91	6.12	0.76	0.23	0.955	0.56
		A42	8.5	6.37	5.59	8.79	0.75	0.685	0.295	0.895
		A43	5.29	8.95	5.25	8.93	0.145	0.975	0.125	0.965
		A44	6.63	8.69	7.85	8.98	0.815	0.845	0.425	0.99
		A45	7.11	8.65	5.51	5.2	0.055	0.825	0.255	0.1
	A5−	A51	6.77	8.77	5.3	8.45	0.885	0.885	0.15	0.725
		A52	5.03	5.59	6.18	5.73	0.015	0.295	0.59	0.365
		A53	8.53	9	8.24	8.81	0.765	0	0.62	0.905
		A54	6.44	6.54	7.8	8.13	0.72	0.77	0.4	0.565

(3) Calculation of membership function values for catastrophe progression: The first-level indicator of the personnel risk included four second-level indicators, corresponding to a butterfly catastrophe. The importance ranking of the indicators was $A12 > A13 > A14 > A11$, and it was a complementary catastrophe system. Therefore,

$$x_{A1}^{1} = \frac{1}{4}\left(\sqrt{A12} + \sqrt[3]{A13} + \sqrt[4]{A14} + \sqrt[5]{A11}\right) = 0.629 \tag{20}$$

The first-level indicator of the management risk included three second-level indicators, corresponding to a wigwam catastrophe. The importance ranking of the indicators was $A24 > A22 > A21 > A23 > A25$, and it was a complementary catastrophe system. Therefore,

$$x_{A2}^{1} = \\ = \frac{1}{5}\left(\sqrt{A24} + \sqrt[3]{A22} + \sqrt[4]{A21} + \sqrt[5]{A23} + \sqrt[6]{A25}\right) = 0.679 \tag{21}$$

The first-level indicator of the material risk included three second-level indicators, corresponding to a coattail catastrophe. The importance ranking of the indicators was $A31 > A32 > A33$, and it was a non-complementary catastrophe system. Therefore,

$$x_{A3}^{1} = \min\left(\sqrt{A32}, \sqrt[3]{A31}, \sqrt[4]{A34}\right) = 0.620 \tag{22}$$

The first-level indicator of the machine risk included five second-level indicators, corresponding to a wigwam catastrophe. The importance ranking of the indicators was $A32 > A41 > A44 > A45 > A42 > A43$, and it was a complementary catastrophe system. Therefore,

$$x_{A4}^{1} = \frac{1}{5}\left(\sqrt{A41}, \sqrt[3]{A44}, \sqrt[4]{A45} + \sqrt[5]{A42} + \sqrt[6]{A43}\right) = 0.792 \tag{23}$$

The first-level indicator of the environmental risk included four second-level indicators, corresponding to a butterfly catastrophe. The importance ranking of the indicators was $A51 > A54 > A52 > A53$, and it was a non-complementary catastrophe system. Therefore,

$$x_{A5}^{1} = \min\left(\sqrt{A51}, \sqrt[3]{A54}, \sqrt[4]{A52}, \sqrt[5]{A53}\right) = 0.350 \tag{24}$$

The risk assessment objectives of the prefabricated building construction included five secondary indicators, corresponding to a wigwam catastrophe. The importance ranking of the indicators was $A3 > A4 > A5 > A2 > A1$, and it was a complementary catastrophe system. The risk assessment result of the prefabricated building construction of X Branch was as follows:

$$x_{A}^{1} = \frac{1}{5}\left(\sqrt{A3} + \sqrt[3]{A4} + \sqrt[4]{A5} + \sqrt[5]{A2} + \sqrt[6]{A1}\right) = 0.867 \tag{25}$$

Following the calculation steps above, the risk assessment result of the prefabricated building construction of Y Branch was as follows:

$$x_{A}^{2} = \frac{1}{5}\left(\sqrt{A3} + \sqrt[3]{A4} + \sqrt[4]{A5} + \sqrt[5]{A2} + \sqrt[6]{A1}\right) = 0.749 \tag{26}$$

The risk assessment result of the prefabricated building construction of Z Branch was as follows:

$$x_{A}^{3} = \frac{1}{5}\left(\sqrt{A3} + \sqrt[3]{A4} + \sqrt[4]{A5} + \sqrt[5]{A2} + \sqrt[6]{A1}\right) = 0.881 \tag{27}$$

The risk assessment result of the prefabricated building construction of W Branch was as follows:

$$x_{A}^{4} = \frac{1}{5}\left(\sqrt{A3} + \sqrt[3]{A4} + \sqrt[4]{A5} + \sqrt[5]{A2} + \sqrt[6]{A1}\right) = 0.756. \tag{28}$$

4.4 Discussion

The following order of the main factors with the highest risk level in the construction of the prefabricated building was obtained through the combination weighting method: quality of prefabricated components (0.091) > standardization degree of prefabricated components (0.086) > environment of installation workspace (0.078). These results indicate that in the construction process of prefabricated construction enterprises, special attention should be paid to the quality of the prefabricated components to prevent sudden changes in the risk during construction. The installation workspace environment of prefabricated building construction enterprises has a greater impact on the risk of prefabricated building construction enterprises. Factors such as the degree of operation specification of lifting personnel (0.024), the degree of operation specification of installation personnel (0.022), and the level of project site management (0.018) have little impact on the risk of prefabricated building construction enterprises.

The evaluation results of four assembly-type construction enterprises affiliated with China State Construction Corporation were obtained, and the risks are ranked as follows: Y branch > W branch > X branch > Z branch. Y branch has a higher risk and should strengthen control measures in terms of the quality of prefabricated components, the standardization level of prefabricated components, and the installation space environment.

5 CONCLUSION

In this study, a novel risk assessment model of prefabricated building construction based on a combination weighting and catastrophe progression method was designed, and the following conclusions were obtained:

(1) Based on the analysis of the accident case reports and existing studies, 52 potential risk indicators were distinguished, and a risk assessment indicator system of prefabricated building construction including five first-level indicators (personnel risk, management risk, material risk, machine risk, and environmental risk) and 21 second-level indicators was obtained. The AHP-CRITIC weight method was used to sort the index weights, and it was found that the quality of the prefabricated components, the standardization degree of the prefabricated components, and the environment of the installation work space are the most important factors affecting the construction risk of prefabricated buildings.

(2) By applying the AHP-CRITIC weight and catastrophe progression method to evaluate four assembly-type construction enterprises, it was found that the Y branch has the highest risk level and the Z branch has the lowest risk level. Based on the above analysis, the Y branch needs to increase management efforts in terms of the quality of prefabricated components, standardization level of prefabricated components, installation workspace environment, machine service life, and risk identification ability of installation personnel. Meanwhile, the AHP-CRITIC weight and catastrophe progression method can reflect the fuzziness of the construction risk of the evaluated project, effectively reduce information loss, and thus make the evaluation results more accurate.

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