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The maturity evaluation of BIM application in prefabricated buildings in power energy projects

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Abstract. With the global emphasis on sustainable development, promoting industrialization, informatization, and low-carbonization has become an urgent requirement for the transformation and upgrading of the construction industry. Prefabricated buildings, when integrated with Building Information Modeling (BIM) technology, offer efficient and environmentally friendly solutions for the construction of power energy projects, as BIM's characteristics of integration, whole-process coverage, visualization, and collaboration make it a powerful driver for industrial transformation. This study develops an evaluation index system for BIM application maturity in prefabricated construction from a whole-life-cycle perspective, covering all stages of power energy projects. The Analytic Network Process (ANP) is employed to determine the weight of each indicator, and the Matter-Element Method is used to construct the maturity evaluation model. The proposed model is applied to a practical engineering case, and the evaluation results identify the current maturity level of BIM application in the project, revealing disparities among lifecycle stages, with certain phases demonstrating lower maturity levels than others. The research provides a systematic framework for assessing BIM application maturity in prefabricated buildings, offering theoretical and practical references to guide the optimization of BIM integration in future projects, thereby supporting high-quality, efficient, and sustainable construction practices.

Keywords: Prefabricated construction, Lifecycle theory, BIM, Maturity.

1 Introduction

With the rapid development of industrialization, problems such as high pollution and high consumption in the construction industry are gradually becoming prominent. According to the "China Building Energy Efficiency Annual Development Research Report (2020)," in 2018, the total energy consumption of the entire construction process was 2.147 billion tce, accounting for 46.5% of the country's total energy consumption [1]. The total carbon emissions from the construction process were 4.93 billion tCO_2, accounting for approximately 51.3% of the country's total carbon emissions. In this context, prefabricated buildings, with their advantages of low pollution, high quality, energy-saving, and efficiency, actively respond to the environmental protection concepts of green buildings and have gained high attention in the construction industry [2]. As of 2020, prefabricated buildings in China accounted for more than 15% of new construction, and in key areas, they had reached over 20%. Prefabricated construction is gradually becoming one of the important directions of China's structural development.

Although prefabricated buildings offer many advantages over traditional structures, their unique characteristics mean they have higher requirements for design, construction, modularization, and other aspects during the building process. Therefore, Building Information Modeling (BIM), an integrated, collaborative, and informational 3D digital technology, is better suited for prefabricated buildings, which involve complex procedures and strict environmental management requirements during construction [3, 4]. By effectively reducing issues such as resource waste, rework, and environmental pollution, BIM encourages a greener and healthier development of prefabricated buildings. Consequently, how to utilize BIM technology to support the scientific advancement of prefabricated buildings has become a key research focus for experts and scholars.

Currently, there has been significant domestic research on the application of BIM in prefabricated buildings [5–10], mainly focusing on specific uses of BIM technology at various stages of prefabrication. These studies greatly

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promote the application and development of BIM technology in the field of prefabricated buildings. However, due to inconsistent levels of BIM implementation in different prefabricated projects, management often appears blind and chaotic. Therefore, to better implement comprehensive and entire-process management of prefabrication, research on BIM application capability is particularly important in the current widespread BIM+prefabrication model. After reviewing the relevant literature, this article ultimately introduces maturity as the theoretical foundation for evaluating BIM application capabilities, aiming to provide a reference for future BIM technology application research.

The earliest research on maturity was started by the Software Engineering Institute's CMM (Capability Maturity Model) model to describe software application capabilities [11]. Its core idea is to make the subject constantly develop and improve through dynamic and continuous changes, making software applications gradually mature and standardized. This theory has gradually been applied to various industries [12]. The earliest research on BIM maturity was mentioned in the "US National BIM Standard" by the American Association of Building Sciences [13]. Its maturity model was improved based on the CMM and the characteristics of BIM, which paved the way for the BIM maturity evaluation model. However, its indicator range is too large for precise assessment. Succar *et al.* [14] proposed five indicators to evaluate the application of BIM maturity from a performance perspective, but the article lacks specific evaluation steps and has no empirical validation, and its feasibility remains to be verified. Wang *et al.* [15] evaluated the application ability of enterprises using BIM technology, but the indicator was limited to enterprises and did not evaluate projects. Chen *et al.* [16] used a structural equation model to study the BIM maturity of construction projects, but lacked an analysis of actual cases. In addition to targeting different objects, BIM maturity applications also have corresponding research on specific BIM application points. Rojas *et al.* [17] and others evaluated the maturity level of BIM application in the project planning and design phases, but the evaluation based on expert interviews and questionnaires lacks quantitative analysis. Zhang and Yu [18] surveyed the BIM application capabilities in construction companies from the perspective of BIM technology, and used examples to verify the feasibility of his evaluation method, but lacked a quantitative analysis of the evaluation method. Luo *et al.* [19] systematically sorted out the index system of BIM application maturity evaluation based on previous research, laying the foundation for subsequent BIM technology application evaluation.

In summary, scholars at home and abroad have conducted relevant research on BIM application maturity, but there are some areas that are not comprehensive enough in the existing research. For example, most research revolves around traditional buildings, lacks quantitative evaluation, or the range of indicators is not comprehensive enough. Therefore, based on previous research, this paper explores the maturity of BIM application in prefabricated buildings and introduces the theory of the whole life cycle to make the indicators more comprehensive. A BIM application maturity evaluation index system that conforms to the characteristics of prefabricated buildings is established. Finally, a matter-element method is used to establish an evaluation model, and cases are introduced for empirical analysis.

2 Evaluation Index System of BIM application maturity in prefabricated construction

2.1 Theoretical basis for establishing indicators

The establishment of this index system starts from the whole life cycle theory, exploring the maturity of BIM application in the entire lifecycle of prefabricated construction. The whole lifecycle refers to considering all aspects of a project or product from the design phase to the final stage. This not only means considering the planning concept during the production phase of the project or product, but also taking into account the operation or maintenance phase of the project or product [20].

2.2 Characteristics of prefabricated construction in the whole lifecycle

At present, the lifecycle theory is widely used in various industries. Lifecycle theory, first developed within systems engineering [21], provides a structured framework for managing projects across all stages, from conception and design to operation and decommissioning. In the construction industry, it has been widely applied to ensure that decision-making at each stage considers its long-term economic, environmental, and operational impacts (ISO 15686-5:2017). This holistic perspective is particularly valuable in prefabricated construction, where multiple stakeholders must coordinate across design, manufacturing, transportation, assembly, and maintenance phases. Integrating lifecycle theory into BIM maturity evaluation ensures that assessment indicators capture the continuity of information, collaboration efficiency, and performance outcomes throughout the entire process [22]. This makes lifecycle theory a theoretically sound and practically relevant foundation for constructing the evaluation index system in this study.

Starting from the basis of prefabricated construction, its lifecycle refers to the design phase, production and transportation phase, construction phase, and operation and maintenance phase of prefabricated construction. The main tasks in each phase are shown in Figure 1.

2.3 Evaluation index of BIM application maturity in prefabricated construction

Based on a literature review, key points of BIM technology application in the entire lifecycle of prefabricated construction have been summarized. After referencing related standard documents such as the "Civil Building Information Model Design Standards" and the "Guidance on Promoting the Application of Building Information Models", the key points of BIM technology application in prefabricated

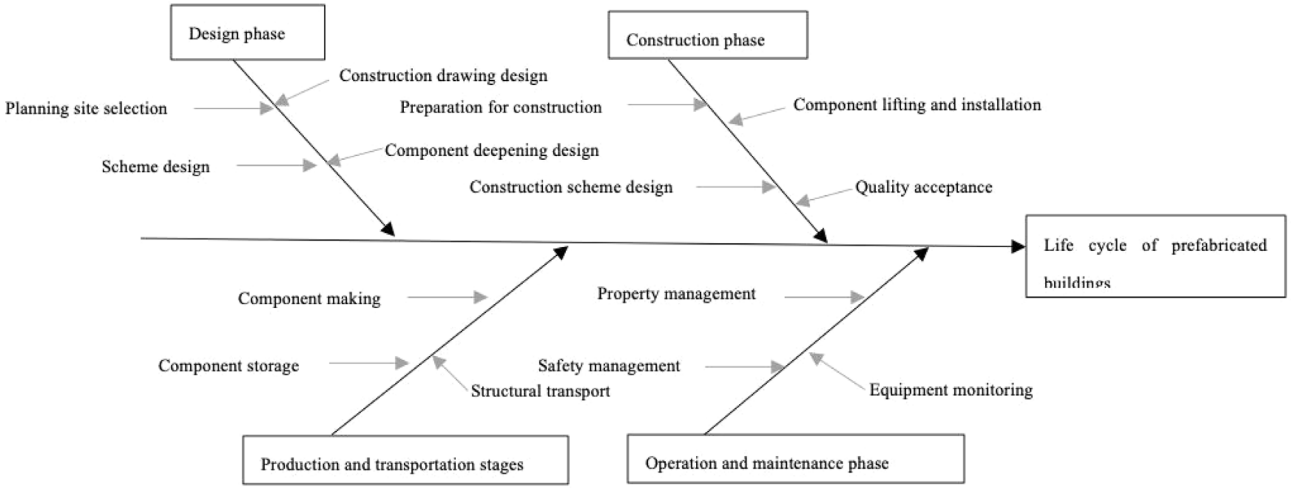

Figure 1. Fishbone diagram of the whole life cycle of prefabricated buildings.

Table 1. Evaluation index system of BIM application maturity of prefabricated buildings.

Target layer	Criteria layer	Indicator layer
Prefabricated building BIM application maturity evaluation index A	Design phase B1	Information synergy C11
		Construction drawing optimization C12
		Component deepening design C23
		3D modeling design C24
	Production and transportation stage B2	Component information ordering management C21
		Component quality control C22
		Component production scheduling C23
		Component transportation information management C24
	Construction phase B3	Data integration management C31
		Construction progress information management C32
		Environmental Monitoring Management C33
		Engineering quantity information management C34
		Construction site planning simulation C35
	Operation and maintenance phase B4	Operation and maintenance system C41
		Key position monitoring and management C42
		Space Operations and Management C43

construction have been supplemented to ensure the integrity and comprehensiveness of the BIM technology application key points, which are used as the evaluation index system for the BIM application maturity in prefabricated construction [23]. At the same time, an expert survey method was employed, inviting experts to discuss and refine the scientificity and consistency of the index system, ultimately determining the evaluation index system for BIM application maturity in prefabricated construction.

Based on the analysis of the whole lifecycle of prefabricated construction and the evaluation index system determined through the literature review method and expert survey method, the evaluation index system is shown in Table 1.

2.4 Maturity evaluation standards

Maturity evaluation levels are determined according to different evaluation models. Some existing maturity evaluation levels include the iBIM model developed by Bew [24], which sets four levels from 0 to 3 and provides division and characteristic descriptions for each level. Succar *et al.* divides maturity into five levels in his BIM maturity evaluation model: initial level, definable level, management level, integrated level, and optimization level. The IU BIM evaluation model, developed by Indiana University, categorizes maturity into stages of progressing towards BIM, recognizing BIM, the silver stage, the gold stage, and the idealized stage. This study, referencing the existing levels of

classification and considering the characteristics and practicalities of prefabricated construction, identifies the development process of BIM technology in the full life cycle of prefabricated construction by dividing the BIM application maturity in prefabricated construction into five stages: initial stage, development stage, mature stage, and optimization stage. The level features of each stage are shown in Table 2.

The BIM application maturity evaluation of prefabricated buildings needs to convert the above qualitative indicators into quantitative indicators and divide prefabricated buildings into different maturity levels according to the evaluation results, which is conducive to understanding the current BIM application maturity, and put forward some development suggestions and improvement measures for prefabricated buildings according to the results. Therefore, this paper first uses Analytic Network Process (ANP) to determine the weight, and then constructs the evaluation model of BIM application maturity by the matter-element method.

With the increasing adoption of Internet of Things (IoT) devices, real-time data acquisition has become an essential component of construction project monitoring. Edge Intelligence, which combines edge computing with artificial intelligence, provides a low-latency and secure approach to process and analyze data close to the source. In the context of BIM maturity evaluation for prefabricated construction, Edge Intelligence can be seamlessly integrated into the assessment framework to enhance both timeliness and accuracy. Specifically, data from Radio Frequency Identification (RFID) tags, IoT sensors, Unmanned Aerial Vehicle (UAV) photogrammetry, and on-site cameras can be processed locally at edge nodes to generate real-time progress tracking, component installation quality assessments, and safety compliance checks. These processed results can then be fed directly into relevant evaluation indicators – such as "construction progress information control" and "construction site planning simulation" – within the BIM maturity model.

For example, in a prefabricated building project, an edge-enabled BIM module can automatically compare actual construction progress against the planned BIM schedule by processing UAV-captured images at the site. Deviations are detected and scored locally, allowing the BIM maturity evaluation system to dynamically update stage-specific maturity ratings. This not only reduces the reliance on manual inspections but also ensures that the maturity assessment reflects real-world conditions in near real time. By embedding Edge Intelligence into the maturity evaluation process, stakeholders can make informed decisions promptly, address emerging issues efficiently, and continuously improve the overall BIM application level in prefabricated projects [25].

3 The index weight is determined based on ANP

Compared with the hierarchical structure of AHP (Analytic Hierarchy Process), the network hierarchy of ANP has a hierarchical structure and internal loop hierarchy, and the hypermatrix operation is used to make practical decision analysis of the complex relationship between the elements with internal dependence and feedback effects. Figure 2 shows the hierarchy.

Although the ANP and matter-element analysis have been widely applied in engineering evaluation research, most prior studies have tended to use these methods either independently or without adaptation to the characteristics of BIM-enabled prefabricated construction. In this study, ANP is integrated with matter-element analysis within a lifecycle-based evaluation framework specifically designed for BIM application maturity assessment. This integration has three notable innovations: (1) the evaluation index system is constructed from a full lifecycle perspective (design, production, construction, and operation/maintenance), ensuring a more comprehensive coverage than stage-specific models in previous studies; (2) the ANP method is employed not only to determine indicator weights considering interdependencies among factors, but also to improve the robustness of subjective judgments through consistency testing, addressing the limitations of over-simplified weighting schemes in earlier works; and (3) qualitative maturity indicators are transformed into quantitative correlation degrees using matter-element analysis, enabling objective measurement of maturity levels and identification of targeted improvement measures. This tailored integration offers a more holistic and actionable maturity evaluation compared to conventional ANP or matter-element models [26, 27].

3.1 Construct the judgment matrix

During the judgment matrix analysis, the scale method of 1–9 is used to assign quantitative values and compare the relative importance of elements. Table 3 shows the meanings of the scale of 1–9, and Table 4 shows the judgment matrix.

3.2 Consistency test

When people make pairwise comparisons of relevant factors of the problem, it is difficult to ensure that the judgment before and after is completely consistent. In order to avoid judgment error, we need to carry out the consistency test of indicators.

The maximum characteristic root $\lambda_{\max}$ is calculated according to the judgment matrix, and its calculation formula is shown as (1):

$$\lambda_{\max} = \frac{1}{n}\sum_{i=1}^{n}\frac{(\mathrm{AW})_i}{W_i}. \tag{1}$$

The calculated $\lambda_{\max}$ is substituted into the formula to calculate the consistency index (CI). The calculation formula of the consistency index (CI) is shown as (2):

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n-1}. \tag{2}$$

Table 2. Rank feature.

Maturity level	Description	
Primary stage	Design phase	Managers do not pay attention to BIM, BIM equipment is not complete, three-dimensional modeling is relatively simple, and cannot be applied.
	Production and transportation stages	The production stage is chaotic, there is no streamlined production process, and material waste is serious. The transport phase is simple and not integrated with IoT technology.
	Construction phase	The BIM application environment is chaotic, the construction process is rough, the construction site cannot be quickly and accurately positioned, and the site pollution is serious.
	Operation and maintenance phase	Information exchange and data storage depend on written materials.
Initial stage	Design phase	Managers initially formed a BIM team, BIM software was used uniformly, 3D modeling and visualization were enhanced, and simple collision detection could be carried out.
	Production and transportation stages	In the production stage, a prefabricated plant is built, and there are simple production steps. The transport phase interacts with the Internet and has a transport plan based on BIM technology.
	Construction phase	The BIM application environment has been initially formed, and the national policy encourages the construction site to use BIM5D technology for standardized construction.
	Operation and maintenance phase	BIM documents are used for the handover between the construction phase and the operation and maintenance phase to provide the required data and data updates for the operation and maintenance phase.
Development stage	Design phase	Managers establish project-level BIM teams, introduce BIM software that can carry out in-depth design, carry out component in-depth design in 3D modeling, and use Revit MEP for pipeline design and other optimization.
	Production and transportation stages	The production stage has a mature prefabrication factory, with the whole process of assembly line production equipment. In the transportation stage, information query of component information transportation process can be carried out based on the Internet of Things.
	Construction phase	The application of BIM in the assembly industry has a uniform trend. BIM visualization and PC animation are used for accurate construction in the construction process, and construction simulation is used to deal with and prevent hidden nodes in advance, and preliminary environmental indicators are monitored.
	Operation and maintenance phase	In property management, BIM software is used to connect with the corresponding equipment, monitor the equipment in real time, and record the operation data, such as energy consumption and performance.
Mature stage	Design phase	The enterprise improves BIM organization and carries out training, and employees learn BIM skills in depth. 3D design of PC components and in-depth design of node assembly can be realized in 3D modeling.
	Production and transportation stages	The production stage is standardized, and the whole production cycle can be quantified statistically. During the transportation phase, the transportation state of components can be statistically analyzed based on the Internet of Things.
	Construction phase	BIM is well applied in the prefabricated construction stage. During the construction process, a two-dimensional code will be used to view installation information. For complex nodes, installation guidance information will be pre-stored by RFID technology, and there is a complete monitoring system for the site environment.
	Operation and maintenance phase	BIM technology and RFID technology are combined to ensure that timely, accurate, and effective information can be obtained. And intelligent monitoring between buildings can be carried out through BIM.

(Continued on next page)

Table 2. (Continued)

Maturity level	Description	
Optimization phase	Design phase	The company has formed an enterprise-level BIM organization, and 3D modeling can be visualized and interactive, and animation simulation and dosage statistics can be carried out.
	Production and transportation stages	In the production stage, RFID technology is introduced to query information and update information in real time. In the transportation phase, RFID technology is combined to realize real-time updates and information upload of transportation information.
	Construction phase	The application of BIM in the assembly construction stage is perfect; the installation information can be updated in real time using RFID technology, and the information can be synchronized with the BIM model, and there is a complete green environmental management system.
	Operation and maintenance phase	BIM technology is used to analyze the safety, durability, and other performance of the prefabricated structure, and has a perfect early warning mechanism.

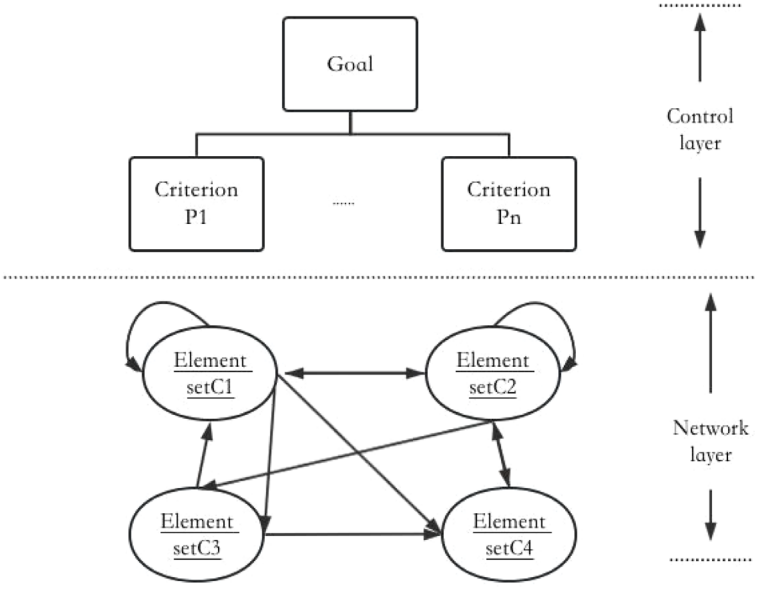

Figure 2. ANP structure.

Table 3. Importance of judgment matrix.

Serial number	Importance index	a_{ij}
1	Elements i and j are equally important	1
2	i element is slightly more important than j element	3
3	The i element is significantly more important than the j element	5
4	Element i is more important than element j	7
5	i element is more important than j element	9
6	i element is slightly less important than j element	1/3
7	The i element is significantly less important than the j element	1/5
8	It doesn't matter that i element is stronger than j element	1/7
9	The i element is extremely less important than the j element	1/9

Table 4. Judgment matrix $\boldsymbol{P}$.

Overall objective A	Criterion B_1	Criterion B_2	Criterion B_3	$\cdots$	Criterion B_n	Weight W
Criterion B_1	1	a_{12}	a_{13}	$\cdots$	a_{1n}	W_1
Criterion B_2	a_{21}	1	a_{23}	$\cdots$	a_{2n}	W_2
Criterion B_3	a_{31}	a_{32}	1	$\cdots$	a_{3n}	W_3
$\vdots$	$\vdots$	$\vdots$	$\vdots$	1	$\vdots$	$\vdots$
Criterion B_n	a_{n1}	a_{n2}	a_{n3}	$\cdots$	1	W_n

Table 5. Average Random Consistency Index (RI) values.

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.52	0.89	1.12	1.26	1.36	1.41	1.46	1.49

Then the consistency test is carried out according to the calculated consistency index CI. The formula for the consistency test is shown in equation (3):

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}}. \tag{3}$$

Among them, if RI < 0.1, it is considered that the consistency test of the judgment matrix passes; otherwise, the consistency test fails. Table 5 shows the values of the average random consistency indicator RI.

3.3 Construct an unweighted supermatrix

Each element in $C_j$is taken as the sub-criterion, and pairwise comparison is made with each element in group C_i and group C_j. Finally, the normalized eigenvectors of each judgment matrix are summarized in matrix $\boldsymbol{W_{ij}}$.

$$\boldsymbol{W_{ij}} = \begin{pmatrix} W_{i1}^{j1} & W_{i1}^{j2} & \cdots & W_{i1}^{jn_j} \\ W_{i2}^{j1} & W_{i2}^{j2} & \cdots & W_{i2}^{jn_j} \\ \vdots & \vdots & \cdots & \vdots \\ W_{in_1}^{j1} & W_{in_2}^{j2} & \cdots & W_{in_j}^{jn_j} \end{pmatrix}. \tag{4}$$

The unweighted supermatrix $\boldsymbol{W_s}$ is:

$$\boldsymbol{W_s} = \begin{array}{c} \\ \\ C_1 \\ \\ C_N \\ \\ \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & & & C_N \end{array} \\ \begin{array}{cccc} e_{11} & e_{11}e_{12}\ldots e_{1n_1} & \cdots & e_{N_1}e_{N_2}\ldots e_{N_{n_N}} \end{array} \\ \begin{pmatrix} \boldsymbol{W_{11}} & \boldsymbol{W_{12}} & \cdots & \boldsymbol{W_{1N}} \\ \boldsymbol{W_{21}} & \boldsymbol{W_{22}} & \cdots & \boldsymbol{W_{2N}} \\ \vdots & \vdots & & \vdots \\ \boldsymbol{W_{N1}} & \boldsymbol{W_{N2}} & \cdots & \boldsymbol{W_{NN}} \end{pmatrix} \end{array} \begin{array}{l} \\ \\ e_{12} \\ \vdots \\ e_{11} \\ e_{12} \\ \vdots \end{array}. \tag{5}$$

3.4 Construct a weight supermatrix

Taking P_s as the main criterion and group C_j as the secondary criterion, pair-based comparison of the groups of elements is carried out to construct a judgment matrix $\boldsymbol{a_j}$. After normalization, the eigenvector $(\boldsymbol{a_{1j}}, \boldsymbol{a_{2j}}, \cdots, \boldsymbol{a_{Nj}})^T$ is obtained. The normalized eigenvector is as follows:

$$\boldsymbol{a_j} = \begin{array}{c} \\ \boldsymbol{C_1} \\ \boldsymbol{C_2} \\ \vdots \\ \boldsymbol{C_N} \end{array} \begin{array}{c} \begin{array}{cccc} \boldsymbol{C_1} & \boldsymbol{C_2} & \ldots & \boldsymbol{C_N} \end{array} \\ \begin{pmatrix} \boldsymbol{a_{11}^j} & \boldsymbol{a_{12}^j} & \ldots & \boldsymbol{a_N^j} \\ \boldsymbol{a_{21}^j} & \boldsymbol{a_{22}^j} & \ldots & \boldsymbol{a_{2N}^j} \\ \vdots & \vdots & & \vdots \\ \boldsymbol{a_{N1}^j} & \boldsymbol{a_{N2}^j} & \cdots & \boldsymbol{a_{NN}^j} \end{pmatrix} \end{array}, \tag{6}$$

Thus, the weight matrix $\boldsymbol{A_s}$ reflecting the relationship between elements under a certain criterion can be obtained.

$$\boldsymbol{A_s} = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1N} \\ a_{21} & a_{22} & \cdots & a_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ a_{N1} & a_{N2} & \cdots & a_{NN} \end{pmatrix}. \tag{7}$$

3.5. Obtain the limit supermatrix

The weight supermatrix $\boldsymbol{W_s^w} = A_s W_s$ can be obtained. In order to better reflect the relationship between elements, the iteration of the supermatrix is used to reflect that:

$$W_s^l = \lim_{k\to\infty} W^k. \tag{8}$$

4 BIM maturity evaluation model based on the matter-element method

Matter-element analysis is a subject between mathematics and experiment initiated by Professor CAI Wen in 1983 [28]. The basic concept of matter element is: the thing to

be evaluated is N, the evaluation feature is C, and the characteristic quantity value is X, and the ordered combination $= (N, C, X)$ is the basic element to describe the thing, referred to as matter element, denoted as $R = (N, C, X)$. If the thing N has n characteristics $c_1, c_2, \cdots, c_n$, then the corresponding quantity value is $x_1, x_2, \cdots, x_n$ expressed as:

$$R = \begin{vmatrix} N & c_1 & x_1 \\ & c_2 & x_2 \\ & \vdots & \vdots \\ & c_n & x_n \end{vmatrix} = \begin{vmatrix} R_1 \\ R_2 \\ \vdots \\ R_n \end{vmatrix}. \tag{9}$$

4.1 Determine the matter-element matrix of classical domain and segment domain

N_j represents the J-th evaluation category divided, c_i represents the evaluation index (feature) corresponding to the evaluation category N_j, x_j represents the magnitude range corresponding to the evaluation index c_i, that is, (a_{j1}, b_{j1}) represents the magnitude range corresponding to evaluation grade j, that is, the classical domain.

$$R_j = (N_j, c_i, x_j) = \begin{vmatrix} N_j & c_1 & x_{j1} \\ & c_2 & x_{j2} \\ & \vdots & \vdots \\ & c_n & x_{jn} \end{vmatrix} = \begin{vmatrix} N_j & c_1 & (a_{j1}, b_{j1}) \\ & c_2 & (a_{j2}, b_{j2}) \\ & \vdots & \vdots \\ & c_n & (a_{jn}, b_{jn}) \end{vmatrix}. \tag{10}$$

If N_j is used to represent the whole evaluation level, C_i is used to represent the evaluation index of thing N, and V_p is used to represent the value range of the index C_n, then the section field is:

$$R_p = (N_p, C_i, V_p) = \begin{vmatrix} N_p & c_1 & (a_{p1}, b_{p1}) \\ & c_2 & (a_{p2}, b_{p2}) \\ & \vdots & \vdots \\ & c_n & (a_{pn}, b_{pn}) \end{vmatrix}. \tag{11}$$

4.2 Determine the object element to be evaluated

The object to be evaluated, the evaluation index, and the corresponding value of the index are represented by the matter element, where c_i represents the i-th evaluation index ($i = 1, 2, \ldots n$), x_i represents the quantity value of c_i of the object to be evaluated, that is, the specific data obtained from the analysis of the object to be assessed.

$$R_x = (N_x, c_i, x_i) = \begin{vmatrix} N_x & c_1 & x_1 \\ & c_2 & x_2 \\ & \vdots & \vdots \\ & c_n & x_n \end{vmatrix} = \begin{vmatrix} R_1 \\ R_2 \\ \vdots \\ R_n \end{vmatrix}. \tag{12}$$

Determine the correlation function and correlation degree of each index of the things to be evaluated.

$$\text{Correlation function } K_j(c_i) = \begin{cases} \dfrac{-\rho(x_i, X_{ji})}{|X_{j1}|}, X_i \in X_{ji} \\ \dfrac{\rho(x_i, X_{ji})}{\rho(x_i, X_{pi}) - \rho(x_j, X_{ji})}, X_i \notin X_{ji} \end{cases} \tag{13}$$

4.3 Calculate the comprehensive correlation degree and determine the comprehensive evaluation level

The comprehensive correlation degree $K_j(N_x)$ of the object N_x with respect to grade j, it is:

$$K_j(N_x) = \sum_{i=1}^{n} \omega_i K_j(X_i). \tag{14}$$

Among them:

When $0 \le K_j(N_x) \le 1$, note the object to be evaluated meets the level requirements. The larger the value, the closer it is to the level standard.

When $-1 < K_j(N_x) < 0$, note that the object to be evaluated does not meet the level requirements, but the object to be evaluated can be converted into a standard object, and the smaller the value, the easier the conversion.

When $K_j(N_x) < -1$, indicates that the object to be evaluated does not meet the grade requirements and does not have the conditions to be converted into evaluation standards.

5 Practical engineering case

5.1 Project overview

A prefabricated building project A in Guangzhou has a total of 12 towers, among which C1–C10 is a prefabricated building with a total area of 259,261.2 m^2. Each tower has 33 floors above ground and 3 floors below ground. The second floor and above are assembled structures, and the prefabricated components include external walls, internal partitions, laminated panels, stairs, and bay Windows, with an assembly rate of 58.36%. This study selects this project as the case due to its representative nature in the field of prefabricated construction and its comprehensive application of BIM technology across the design, production, and construction stages. The project involves multiple stakeholders, complex coordination processes, and diverse BIM application scenarios, which make it an ideal subject for evaluating BIM application maturity. Applying the proposed ANP–matter-element evaluation model to this project not only verifies the model's effectiveness in real-world settings but also demonstrates its scalability for other prefabricated construction projects with similar lifecycle characteristics.

Table 6. Expert judgment-based weight assignment.

	Degree of judgment basis			Degree of judgment basis	Degree of judgment basis
Judgment basis	Good	Medium	Poor	Very Familiar	1.0
Practical experience	0.5	0.4	0.3	Familiar	0.8
Theoretical analysis	0.3	0.2	0.1	Generally familiar	0.6
Domestic and international references	0.1	0.1	0.1	Unfamiliar	0.4
Subjective judgment	0.1	0.1	0.1	Very unfamiliar	0.2

Table 7. Index weight.

Criteria layer	Indicator layer	Weight
Design phase B1	Information synergy C11	0.28
	Construction drawing optimization C12	0.16
	Component deepening design C23	0.47
	3D modeling design C24	0.10
Production and transportation stage B2	Component information ordering management C21	0.20
	Component quality control C22	0.22
	Component production scheduling C23	0.46
	Component transportation information management C24	0.12
Construction phase B3	Data integration management C31	0.24
	Construction progress information management C32	0.34
	Environmental Monitoring Management C33	0.13
	Engineering quantity information management C34	0.20
	Construction site planning simulation C35	0.1
Operation and maintenance phase B4	Operation and maintenance system C41	0.3
	Key position monitoring and management C42	0.54
	Space Operations and Management C43	0.16

The expert consultation survey in this study consists of three parts. The first part collects the basic information of the experts, including their age, affiliated organization, professional title, position, field of work, and years of experience. The second part is used to determine the authority coefficient of the experts. The level of authority is generally determined by two factors: the basis on which the expert makes judgments about the plan, and the expert's familiarity with the issue. The quantitative values are shown in Table 6. The authority coefficient (Cr) is calculated as the arithmetic mean of the judgment basis coefficient (Ca) and the familiarity coefficient (Cs), according to the formula $Cr = (Ca + Cs)/2$. Generally, $Cr > 0.7$ is considered acceptable. The third part contains the expert consultation content, which includes the allocation of importance weights to the indicators, with the total weight summing to 100%.

This study plans to use a questionnaire survey method to invite BIM-related experts as the survey subjects. Eventually, 44 experts agreed to participate in the research.

After statistical calculation, in this study, the expert consultation $Ca = 0.9$, $Cs = 0.9$, and the average expert authority Cr is $(0.9 + 0.9)/2 = 0.9$. The research results are greater than 0.7, indicating that the results obtained from the expert consultation in this study are authoritative.

5.2 Indicator weights

Yaanp software is used to calculate the weights, which are shown in Table 7.

As shown in Table 8, the CR values of each indicator meet the consistency requirements.

5.3 Maturity evaluation model

5.3.1 Determine the maturity level domain

According to the maturity evaluation level, the BIM application maturity level in assembly type is divided into $U = \{U1, U2, U3, U4, U5\} = \{$primary stage, initial stage, development stage, mature stage, optimization stage$\}$.

5.3.2 Determine classical domain and section domain

The classical domain matter-element matrix $\boldsymbol{R_{01}}$, $\boldsymbol{R_{02}}$, $\boldsymbol{R_{03}}$, $\boldsymbol{R_{04}}$, $\boldsymbol{R_{05}}$ and section domain matter-element matrix $\boldsymbol{R_p}$ established according to the maturity level domain and the evaluation factor set are shown in Table 9.

The scoring intervals for each maturity stage were determined based on established BIM maturity evaluation frameworks and refined through two rounds of Delphi surveys with ten experts who each have over ten years of

Table 8. Consistency test results of judgment matrices.

Matrix	n	λ_{max}	CI	RI	CR
B1 (Design phase)	4	4.0000	0.000000	0.89	0.000000
B2 (Production and transportation)	4	4.0000	0.000000	0.89	0.000000
B3 (Construction phase)	5	5.0000	0.000000	1.12	0.000000
B4 (Operation and maintenance)	3	3.0000	0.000000	0.52	0.000000

Table 9. Application maturity evaluation of classical domain and section domain.

Index	Primary stage(R_{01})	Initial stage(R_{02})	Development stage(R_{03})	Mature stage (R_{04})	Optimization phase (R_{05})	R_p
C_{11}	0–60	60–70	70–80	80–90	90–100	0–100
C_{12}	0–60	60–70	70–80	80–90	90–100	0–100
C_{13}	0–60	60–70	70–80	80–90	90–100	0–100
C_{14}	0–60	60–70	70–80	80–90	90–100	0–100
C_{21}	0–60	60–70	70–80	80–90	90–100	0–100
C_{22}	0–60	60–70	70–80	80–90	90–100	0–100
C_{23}	0–60	60–70	70–80	80–90	90–100	0–100
C_{24}	0–60	60–70	70–80	80–90	90–100	0–100
C_{31}	0–60	60–70	70–80	80–90	90–100	0–100
C_{32}	0–60	60–70	70–80	80–90	90–100	0–100
C_{33}	0–60	60–70	70–80	80–90	90–100	0–100
C_{34}	0–60	60–70	70–80	80–90	90–100	0–100
C_{35}	0–60	60–70	70–80	80–90	90–100	0–100
C_{41}	0–60	60–70	70–80	80–90	90–100	0–100
C_{42}	0–60	60–70	70–80	80–90	90–100	0–100
C_{43}	0–60	60–70	70–80	80–90	90–100	0–100

experience in prefabricated construction and BIM application. These experts were asked to propose and adjust threshold values for each stage to ensure practical applicability. The relatively broad ranges (e.g., 60–70 for the initial stage) are designed to accommodate variability in project characteristics and the inherent subjectivity of expert scoring, while preventing abrupt changes in maturity classification due to small score differences. This approach enhances robustness and comparability across different projects [29].

5.3.3 Determine the object element to be evaluated

The classical domain matter-element matrix $\boldsymbol{R_{01}}$, $\boldsymbol{R_{02}}$, $\boldsymbol{R_{03}}$, $\boldsymbol{R_{04}}$, $\boldsymbol{R_{05}}$ and section domain matter-element matrix $\mathbf{R_p}$ established according to the maturity level domain and the evaluation factor set are shown in Table 7 below:

This paper adopts the expert survey method, inviting 10 relevant experts engaged in the assembly industry and the management personnel of the participating parties to score the BIM. The scoring interval is [0, 100], and finally calculates the average value according to the scoring results of the experts. Finally, the object element matrix $\boldsymbol{R_x}$ of BIM application maturity evaluation for an assembly project in Guangzhou is determined as follows:

$$\boldsymbol{R_x} = \begin{bmatrix} N & C_{11} & 66 \\ & C_{12} & 84 \\ & C_{13} & 82 \\ & C_{14} & 73 \\ & C_{21} & 85 \\ & C_{22} & 87 \\ & C_{23} & 79 \\ & C_{24} & 84 \\ & C_{31} & 71 \\ & C_{32} & 65 \\ & C_{33} & 79 \\ & C_{34} & 84 \\ & C_{35} & 62 \\ & C_{41} & 72 \\ & C_{42} & 71 \\ & C_{43} & 71 \end{bmatrix}. \quad (15)$$

Table 10. Correlation degree of secondary index.

Secondary index	K_{01}	K_{02}	K_{03}	K_{04}	K_{05}	Evaluation level
C_{11}	−0.15	0.4	−0.105	−0.292	−0.414	Initial stage
C_{12}	−0.6	−0.467	−0.200	0.4	−0.273	Mature stage
C_{13}	−0.55	−0.400	−0.100	0.2	−0.308	Mature stage
C_{14}	−0.325	−0.100	0.3	−0.206	−0.386	Development stage
C_{21}	−0.625	−0.500	−0.250	0.5	−0.250	Mature stage
C_{22}	−0.675	−0.567	−0.350	0.3	−0.188	Mature stage
C_{23}	−0.475	−0.300	0.1	−0.045	−0.344	Development stage
C_{24}	−0.6	−0.467	−0.200	0.4	−0.273	Mature stage
C_{31}	−0.275	−0.033	0.1	−0.237	−0.396	Development stage
C_{32}	−0.125	0.5	−0.125	−0.300	−0.417	Initial stage
C_{33}	−0.475	−0.300	0.1	−0.045	−0.344	Development stage
C_{34}	−0.6	−0.467	−0.2	0.4	−0.273	Mature stage
C_{35}	−0.05	0.2	−0.174	−0.321	−0.424	Initial stage
C_{41}	−0.3	−0.067	0.077	−0.222	−0.391	Development stage
C_{42}	−0.275	−0.033	0.036	−0.237	−0.396	Development stage
C_{43}	−0.275	−0.033	0.036	−0.237	−0.396	Development stage

Table 11. First-level index correlation degree.

Secondary index	K_{01}	K_{02}	K_{03}	K_{04}	K_{05}	Evaluation level
C_{11}	−0.15	0.4	−0.105	−0.292	−0.414	Initial stage
C_{12}	−0.6	−0.467	−0.200	0.4	−0.273	Mature stage
C_{13}	−0.55	−0.400	−0.100	0.2	−0.308	Mature stage
C_{14}	−0.325	−0.100	0.3	−0.206	−0.386	Development stage
C_{21}	−0.625	−0.500	−0.250	0.5	−0.250	Mature stage
C_{22}	−0.675	−0.567	−0.350	0.3	−0.188	Mature stage
C_{23}	−0.475	−0.300	0.1	−0.045	−0.344	Development stage
C_{24}	−0.6	−0.467	−0.200	0.4	−0.273	Mature stage
C_{31}	−0.275	−0.033	0.1	−0.237	−0.396	Development stage
C_{32}	−0.125	0.5	−0.125	−0.300	−0.417	Initial stage
C_{33}	−0.475	−0.300	0.1	−0.045	−0.344	Development stage
C_{34}	−0.6	−0.467	−0.2	0.4	−0.273	Mature stage
C_{35}	−0.05	0.2	−0.174	−0.321	−0.424	Initial stage
C_{41}	−0.3	−0.067	0.077	−0.222	−0.391	Development stage
C_{42}	−0.275	−0.033	0.036	−0.237	−0.396	Development stage
C_{43}	−0.275	−0.033	0.036	−0.237	−0.396	Development stage

5.3.4 Calculate the correlation degree

The matter element to be evaluated is brought into the matter element model, and corresponding calculation results are obtained as shown in Table 10.

The correlation degree of the primary index can be calculated according to the correlation degree of the secondary index, and the results are shown in Table 11.

5.3.5 Result analysis and suggestions

According to the conclusion obtained from the matter-element evaluation model, the BIM application maturity of this assembled project belongs to the mature stage, but its comprehensive correlation degree is 0.003, indicating that although the project has entered the mature stage, it has only entered the mature stage from the development stage, and there is still some distance from complete maturity. At the same time, according to the correlation degree of first-level indicators, the maturity of the construction stage is not enough compared with other stages, and it is still in the initial stage, indicating that some progress in simulation, data processing, and other tasks in the construction stage are not enough to combine with BIM. If the project wants to improve the application maturity of BIM,

we should focus on the improvement of some technical simulation and data processing in the construction stage. From the perspective of the correlation degree of the second-level indicators, design coordination, construction progress information control and management, and construction site planning simulation are still in their infancy, which indicates that during the specific implementation of the project, the participating units have not done enough in the aspects of data sharing and cooperation in the design stage. Meanwhile, the planning of the construction site also relies more on experienced managers. The use of BIM to solve the site layout and progress control is still weak. Therefore, the management and coordination of the project construction site through BIM technology is the entry point for the project to improve the application of BIM.

Based on the evaluation results, targeted recommendations are proposed for different industry stakeholders to enhance BIM application maturity in prefabricated construction. For construction companies, it is essential to strengthen BIM-based construction site planning and simulation capabilities, integrate RFID/IoT technologies for real-time progress tracking, and improve on-site data management systems. For designers, adopting standardized BIM component libraries, enhancing multidisciplinary collaboration through shared BIM platforms, and conducting regular clash detection during the design phase can significantly improve coordination and reduce rework. For government bodies, it is recommended to formulate clear BIM application standards for prefabricated construction, provide training programs to build industry-wide BIM capacity, and introduce incentive policies – such as subsidies or tax reductions – to encourage BIM adoption in key lifecycle stages. Implementing these measures can effectively address the maturity gaps identified in this study and promote more efficient, sustainable, and high-quality prefabricated building projects.

6 Conclusions

Through the analysis of the application of BIM technology in prefabricated buildings, the important position of BIM technology in the future development of prefabricated buildings is revealed. For the construction industry, prefabricated building is a systematic and integrated building that integrates design, production, and construction. BIM technology has the ability to carry, analyze, and operate building information at all stages, and at the same time provides a collaborative platform to enable the information of each link of prefabricated buildings to be effectively interactive, so as to realize the collaborative work among various professions, improve efficiency, and reduce the waste of resources. Therefore, in the process of combining BIM technology with prefabricated buildings, the maturity of BIM application plays an important role in the development of prefabricated buildings.

Combined with the current research of experts and scholars on prefabricated buildings + BIM technology, it can be found that most of the studies are on the practical application of BIM technology in prefabricated buildings, but there are few studies on its application effect, ability, maturity, and other issues. Based on the life cycle theory, this paper, Research on BIM technology application maturity, was carried out from the design stage of prefabricated buildings to the operation and maintenance stage, and the BIM technology application maturity evaluation system was constructed by combining the Analytic Network Process (ANP) to identify indicators that influence BIM application maturity in prefabrication buildings. At the same time, the BIM application maturity evaluation model was constructed using the matter-element method. The model is applied in combination with the actual case, and the qualitative indicators are fully transformed into quantitative indicators. The analysis of the conclusions is helpful to promote the in-depth application of BIM technology in prefabricated buildings from the key factors, so as to promote the high precision, high quality, and green environmental protection of prefabricated buildings, which is conducive to the flourishing development of prefabricated buildings.

Future research directions include expanding the evaluation framework to cover diverse project types and regions, integrating BIM maturity evaluation with emerging technologies such as Digital Twins and AI for real-time project monitoring, and investigating long-term economic and environmental impacts of BIM adoption in prefabricated construction. These efforts can further enhance the practical value of BIM maturity research and support the sustainable, large-scale development of the prefabricated construction industry.

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Conflicts of interest

The authors declare no conflicts of interest.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material; further inquiries can be directed to the corresponding author/s.

Author contribution statement

Conceptualization, YH.W. and XQ.L.; methodology, YH.W.; software, YH.W.; validation, XQ.L.; formal analysis, XQ.L.; investigation, XQ.L.; resources, XQ.L.; data curation, YH.W.; writing—original draft preparation, YH.W.; writing – review and editing, XQ.L.; visualization, YH.W.; funding acquisition, YH.W. YH.W. and XQ.L., led to writing the article with equal contributions. All authors have read and agreed to the published version of the manuscript.

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