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The Assessment of the Maturity of Informatization in Assembly-Building Projects Utilizing the CMM-CME Methodology, Taking a Project in China as an Illustration

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Abstract: Owing to its rapid advancement, information technology has emerged as a critical tool in assembly construction for addressing market demands, improving project quality, and reducing costs. However, the absence of unified informatization standards within the assembly construction industry has led to the adoption of different technologies and systems by various businesses during the development of informatization systems; this has generated issues such as unbalanced development and mutual incompatibility. While researchers have examined these issues, a comprehensive assessment of the maturity of informatization in assembly-building projects is lacking. Assessment of the maturity of informatization can provide evaluation standards and methods for the development of informatization of assembly buildings, explore the important and difficult points of applying informatization technology to assembly buildings, and put forward corresponding countermeasures and suggestions to promote the benign development of informatization of assembly buildings. Therefore, this study strives to develop a model for assessing the maturity of informatization of assembly-building projects. This study begins by determining the level of the maturity level of informatization, key process areas, and key practices for assembly-building projects using the capability maturity model (CMM). On this basis, the maturity evaluation index system was constructed through expert interviews and questionnaires. Furthermore, in order to assign weights to the indicators comprehensively, the ordinal relationship method and entropy weight method were implemented. The evaluation criteria were determined by consulting the relevant literature and expert opinions. Followingly, an evaluation model was established based on the cloud matter element (CME) theory. Finally, a case study demonstrates that the methodology can be utilized to quantify the maturity of project informatization. In conclusion, this study unearths a system for assessing the level of maturity of informatization of assembly-building projects, which provides a valuable reference for promoting the continuous development of the maturity of informatization in assembly-building projects.

Keywords: assembly-building projects; informatization maturity evaluation; capability maturity model; cloud matter element (CME) theory

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1. Introduction

The construction industry contributes significantly to the country's economy [1]. It generates 5–10% of the country's employment and leads to 5–15% growth in gross national product [2]. Construction enterprises in China generated a total output value of CNY 29.3 trillion in 2021, representing a 1.14-fold increase compared to the previous year, 2012. Despite this, the conventional construction model is troubled by a shortage of personnel, low efficiency, inadequate technology, resource waste, and environmental pollution as the economy of the construction sector grows exponentially [3]. To meet these challenges, countries are exploring ways to revolutionize the construction industry; assembly construction is attracting attention as a novel method of building production. Assembled buildings can reduce the reliance on conventional construction modes of labor, conserve resources and energy, mitigate environmental pollution, enhance construction efficiency and building quality, and promote the industry's transformation and upgrading [4].

The construction method of assembly building is founded upon standardized design, factory production, mechanized construction, and information management; thus, this construction method possesses an inherent compatibility with the implementation of information technology. The application of various information technologies will substantially increase the energy efficiency of assembled buildings, improve information collection and communication throughout production, transportation, and on-site assembly, and reduce human error [5]. Currently, the scientific community focuses on the assembly-building informatization and emphasizes the practical application of technology in engineering projects, which allows them to conduct in-depth research on a specific engineering segment or process. Nonetheless, technological enhancement alone is insufficient to advance the informatization of assembly buildings. In order to identify the weaknesses of information technology and propose improvements, it is necessary to evaluate its maturity in assembly buildings. Existing studies on the evaluation of informatization have been abundant with evaluation methods and indicators [6–8]. For example, hospital informatization level evaluation, enterprise informatization performance evaluation, and logistics informatization evaluation. However, a deficiency exists within the construction industry, especially concerning assembly-building projects: the evaluation indexes for the maturity of informatization in assembly-building projects have not yet been systematized. Constantly utilized to evaluate the level of capability maturity across domains, the capability maturity model (CMM) can provide a standardized framework for continuous process improvement [9]. The development of informatization for assembly-building projects is a process of continuous improvement and gradual advancement. The introduction of the capability maturity model can define the capability characteristics of various stages of informatization development, which prompted the organization to transition from a state of chaos and disorder to one of standardization and continuous optimization [10].

To fill these gaps, this research aims to develop an overall evaluation model of the maturity of informatization for assembly-building projects. Specifically, it includes (1) What is the evaluation system of the maturity of informatization of assembly-building projects? (2) What are the criteria for evaluating the maturity of informatization for assembly-building projects? and (3) How can the evaluation of the maturity of informatization for assembly-building projects be realized? This study first discusses the maturity level of informatization for assembly-building projects. The key process areas and key practices in the maturity model were initially identified through an examination of the relevant literature and specification texts. Following the revision and validation of the key practices via expert interviews and questionnaires, the evaluation index system was ultimately constructed. After determining the index weights and evaluation criteria, an evaluation model of informatization maturity of assembly-building projects was constructed through the cloud matter element (CME) theory. The cloud matter element theory is the introduction of the cloud model in the matter element theory, using the fuzzy and random nature of the cloud model; it can solve the evaluation problem of qualitative problems, through the quantitative numerical value to represent the results of the comprehensive evaluation, which can clearly reflect the real characteristics of the evaluation object. The feasibility of the model is then verified with an actual project case. Following the analysis of the findings of the evaluation, recommendations are generated. By identifying the extent of the development of informatization in assembly-building projects and the deficiencies therein, this evaluation method facilitates the formulation of countermeasures to ensure their high-quality development.

The subsequent sections provide descriptions of the literature review, methodology, case study, results and discussion, as well as conclusions.

2. Literature Review

2.1. Assembly Building Project Informatization

Assembly buildings are crucial to achieving the industrialization and informatization of construction; furthermore, the implementation of information technology will significantly improve production efficiency, foster scientific and technological progress, and elevate the efficiency and quality of the project. At present, information technology is extensively employed throughout the entirety of assembly-building projects, including design, production, construction, and administration. For example, the application of building information modeling (BIM) for component damage monitoring [11], the assessment of implied carbon emissions via the Internet of Things (IOT) [12], the implementation of radio frequency signal technology (RFID) to update real-time construction information [13], the utilization of 3D printing technology to print prefabricated components [14], and the optimization of simulations through virtual reality (VR) technology [15]. Additionally, the researchers integrated various information technologies. Gao integrates the application of BIM and geographic information system (GIS) technologies to assess the greenhouse gas emissions of assembled buildings, which provides a reference for assessing the capacity of assembled buildings to conserve energy and reduce emissions [16]. Zhou combines digital twin technology and BIM to monitor risks during assembly building construction and reduce safety hazards [1]. Zeynab integrates VR and RFID information technology to create a regulatory platform system framework capable of risk identification, recording, and pre-alarm processing in real-time [17].

In addition, there are some other informatization technologies applied in assembly-building projects. For example, in the production, transportation, and construction of prefabricated components. Xu established an automatic optimization framework for production scheduling of prefabricated components based on manufacturing process models and genetic algorithms, which improved the operability and accuracy of the production process [18]. Mojtaba develops a tracking and condition monitoring system for damage detection in the transportation of prefabricated components [19]. Xu proposes an assembly building monitoring method based on feature extraction and point cloud segmentation, which can find the quality problems caused by schedule delays and errors in construction in a timely manner [20]. In the progress, safety, and management of the project, Yan uses computer vision technology, the weighted kernel density estimation method, and the labor duration management method to intelligently monitor and evaluate the progress of prefabricated buildings [21]. Shen uses Autodesk Revit 2016 combined with ontology theory to establish a construction monitoring system for prefabricated components to provide timely information for construction safety risk decision making [22]. Yang developed a four-dimensional construction management information model based on industry foundation classes (IFC) and graphical databases, which improved the efficiency of data interoperability and automation of progress analysis, and improved the management of assembled buildings [23]. With the advancement in technology, the construction industry is increasingly incorporating robots, including aerial robots and drones, that facilitate construction site scanning [24]. However, research concerning the informatization of assembly-building projects primarily focuses on the technical level, neglecting an assessment of the overall degree of informatization. Therefore, there is an urgent need to establish a maturity evaluation model for informatization in assembly-building projects so that organizations can gain a comprehensive understanding of the project's information level and make necessary improvements.

2.2. Capability Maturity Model

Originally applied to software development, capability maturity models generally comprise maturity levels, key process areas, and key practices [25]. Owing to its concept of continuous improvement, it is widely used in various fields to provide guidance and pathways for improvement in order to facilitate the evolution of events [26]. In an effort to assist the government in determining how to enhance its public emergency response capability, Wang, for instance, developed a maturity model for public emergency response capability comprised five dimensions [27]. Liao developed a two-dimensional project management maturity model by integrating project business management and information technology [28]. Shen constructed a capacity maturity model to evaluate the performance of low-carbon city practices, which allows policymakers to address specific areas of concern by identifying weaknesses in these practices [29]. Certain researchers have also addressed BIM maturity in the construction industry by developing a BIM capability maturity model, which assesses the degree of advancement and the capabilities of building information modeling (BIM). Lu constructs BIM maturity models to measure the degree of development and level of competence in the application of BIM technology at the project, organization, and industry levels [30]. Sun constructs the BIM application maturity model (BIM-AMM) from the perspectives of technology, social environment, and project participants [31]. Considering the wide range of information technology utilized in assembly-building projects, including but not limited to BIM [32], assessing informatization maturity cannot be considered comprehensive by exclusively considering BIM. The informatization of assembly-building projects involves numerous information technologies and the maturity level can be subdivided. Meanwhile, the informatization of assembly building can continue to expand with technological improvements and extensive applications. The capability maturity model can provide an optimization framework for informatization maturity, avoid developmental blindness through maturity level assessment, and ensure targeted promotion of information technology development. Therefore, the capability maturity model can be effectively employed to assess the maturity of informatization in assembly-building projects.

3. Methodology

3.1. Research Framework

Based on the capability maturity model and the development process, the information technology maturity for assembly-building projects is categorized into four levels. The primary sources of information for key process areas and key practices were obtained from relevant specification texts and the literature on the Web of Science. To validate and revise these key practices, expert interviews and questionnaires were utilized and an indicator evaluation system was constructed based on key process areas and key practices. On this basis, the weights of the indicators are determined through the comprehensive assignment of the ordinal relationship method (G1) and entropy weight method. Subsequently, the development of the evaluation model is grounded in the cloud matter element theory. The feasibility of the model is ultimately verified by an example. The specific research framework is illustrated in Figure 1.

3.2. Classification of the Maturity Level

The approach to the classification of maturity levels is subject to variation. Typically, these levels are categorized into four to six levels based on a detailed description of the developmental process [33]. The maturity of the informatization of an assembly building project reflects its level of information and technology application. Due to the implementation of conventional management and technical methods, earlier projects had limited application of informatization. Information technology is implemented in the construction industry to improve efficiency, as it industrializes and transitions to information technology. In order to solve the issues of resource waste and environmental pollution, the project gradually adopts a greater amount of information technology to form a technical system. With the rapid development of technology, information technology must be constantly updated to secure sustainable development. Utilizing the concept of the division of capability maturity model, the sequential and in-depth development of informatization in assembly-building projects can be categorized into four levels: initiation, development, normative, and continuous optimization. Figure 2 characterized each maturity level as follows.

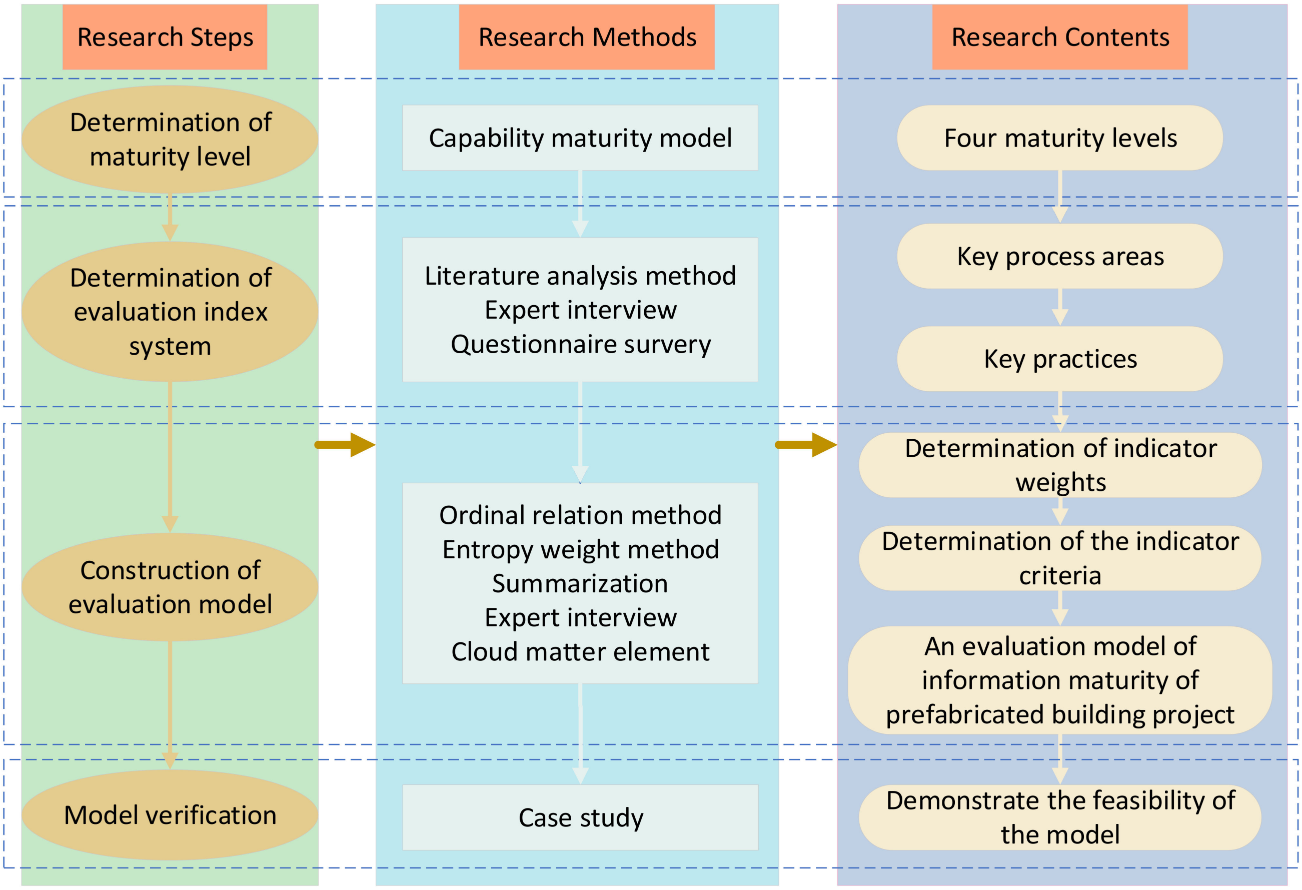

Figure 1. Research framework.

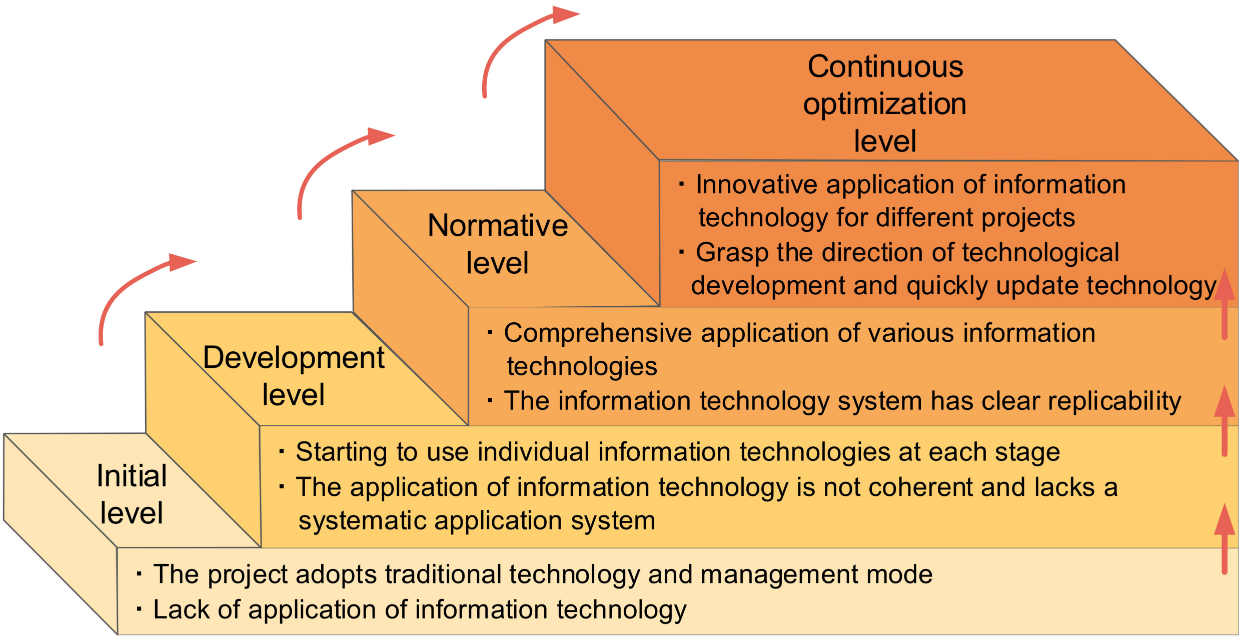

Figure 2. Maturity level and description.

3.3. Construction of the Indicator System

3.3.1. Identification of Key Process Areas

Key process areas are key capability indicators that represent critical maturity levels [25]. A review of the relevant literature revealed that when extracting the key process areas of informatization maturity for assembly-building projects, it was found by analyzing the related assessment literature that the key process areas usually start from the dimensions of time and subject. Liu identified six first-level evaluation indicators from the subject dimensions: personnel, materials, equipment, environment, management, and technology when assessing the safety performance of assembly-building projects in China [34]. With respect to the time dimension, Liang identified the following assessment indicators for the efficiency of the industrialization of assembled residential buildings: standardized design, off-site manufacturing, component transportation, and on-site construction [35]. Despite the variations between these two divisions, the relevant evaluation objects are comprehensively encompassed, with regard to both the time and subject dimensions of the division. The logic is more lucid and the indicators are more comprehensive when time is designated as the primary line and the subject is considered the complement. Therefore, a combination of time and subject dimensions was chosen for the selection of key process areas.

The stages of design, production, and transportation, as well as construction and assembly, comprise the majority of the time dimension of informatization of assembly-building projects. The subject dimensions focus on schedule, cost, quality, personnel, materials, equipment, collaborative management platform construction, and environmental management of the construction site environment. Directly or indirectly, the quality and advancement of assembly-building projects are impacted by the informatization of design, production transportation, and construction assembly. Therefore, the two subject dimension elements of schedule and quality are incorporated into three key process areas. Key process domains such as personnel, materials, machinery and equipment, costs, and environmental protection can be considered relatively independent from one another. They encompass various functions and areas of expertise, necessitate autonomous independent decision-making and control capabilities, utilize non-interfering data, and demand specialized equipment and technical assistance, as well as targeted training and development. Thus, independent management contributes to more flexible, efficient, and professional project management. Collaborative management is an integrated process to improve the management efficiency of all project participants and can also be evaluated independently as a key process area to assess its information technology maturity. In the end, seven key process areas were identified, as detailed in Table 1.

Table 1. Key process areas.

Dimension	Key Process Areas	Hidden Meaning
Time	Design informatization (B1)	BIM forward design enhances efficiency and refinement through BIM technology cloud platforms
	Production and transportation informatization (B2)	Integrated application of BIM, IoT technology and GIS technology
	Construction assembly informatization (B3)	Visualization and virtualization of progress and quality management
Subject	Informatization of personnel, material and machine management (B4)	Real-time monitoring of personnel, materials and equipment, transmission of monitoring data, and dissemination of early warnings
	Environmental management informatization (B5)	Visualization and monitoring of construction sites, automatic warnings, and proactive interventions
	Business management informatization (B6)	Computerization of cost, contract, and procurement management informatization
	Engineering collaborative management informatization (B7)	Establishment of an information platform to facilitate collaborative project administration

3.3.2. Identification of Key Practices

Key Practices are detailed descriptions that specify the precise effort needed to achieve a given level of maturity and correspond directly to the tasks or activities in key process areas. To identify key practices, a literature search was initially conducted in conjunction with key process areas. Web of Science searches were conducted using the following keywords: "building informatization", "intelligent construction", "digital construction", "virtual construction", "intelligent construction site", and "information construction". After analyzing the literature that exhibited a high degree of content similarity with the results of the search and this study, 33 key practices were initially screened. Second, 30 key practices were extracted from the "10 New Technologies in Construction Industry (2017) [36]" issued by the Ministry of Housing and Urban–Rural Development of China in October 2017. Among these, the 10th "informatization technology" covers the majority of the informatization technologies applicable to the construction industry. A total of 17 key practices were deleted and merged through integration with the 33 key practices screened by the literature analysis, resulting in the retention of 46 initial key practices, as shown in Table S1 provided in the Supplementary Materials. The opinions and suggestions of seven experts regarding the initial 46 key practices that were screened were gathered via in-person interviews and telephone conversations; the experts' information is detailed in Table 2. Expert input was integrated to optimize ambiguously stated key practices, thereby preserving their original intent and enhancing comprehensibility, while merging key practices that carry redundant meanings. A total of 28 key practices were retained after refinement, which are detailed in Table 3.

Table 2. Specialist information.

Serial Number	Work Unit	Duties
1	A software company in the construction industry	Product manager
2	China state construction corporation	Manager of informatization department
3	China state construction corporation	Project manager
4	Nanjing forestry university	Associate professor
5	Nanjing forestry university	Professor
6	A construction group	Manager of informatization department
7	A design institute	BIM designer

Table 3. The process of refinement of key practices.

Pre-Perfection	Post-Processing	Pre-Perfection	Post-Processing
1. Extent of application of BIM functionality [37]	The degree of application of BIM design performance (C11)	26. Stockpile planning [38]	Material supervision informatization (C43)
2. BIM collaborative design [39]	BIM collaborative design (C12)	27. A system for engineering resource management [40]	
3. BIM precast splitting [41]	Split design of prefabricated components (C13)	28. Monitoring the safety operations of large equipment [42]	Informatization of machinery and equipment safety monitoring (C44)
4. BIM modeling depth [43]	BIM modeling accuracy (C14)	29. Management of scaffolding engineering informatization safety [44]	
5. BIM deepening design [1]		30. Monitoring on-site for informatization regarding noise and dust [45,46]	Environmental monitoring informatization (C51)
6. BIM software data interactivity [47]	BIM software data interactivity (C15)	31. Linkage applications for dust reduction, noise reduction, and haze reduction [48]	

Table 3. *Cont.*

Pre-Perfection	Post-Processing	Pre-Perfection	Post-Processing
7. Standardized and universal design of components [49]	Standardized design of components (C16)	32. Identification of construction waste vehicles [36]	Informatization of construction waste regulation (C52)
8. Intelligent component production line [50]	Informatization of production equipment (C21)	33. Identification and classification and construction waste [36]	
9. BIM-based scheduling [18]	Component production scheduling informatization (C22)	34. Platforms for the monitoring and management of construction waste [36]	
10. Component transportation costs, route optimization [51]	Informatization of the component transportation program (C23)	35. Project cost data acquisition model [36]	Cost management informatization (C61)
11. IoT technology for component information collection and quality traceability [52]	Informatization of component traceability (C24)	36. An analysis model for price indicator correlation [36]	
12. Visualization of technical briefings [53]	Construction assembly plan informatization (C31)	37. Visualization and analysis of project cost [36]	
13. Construction site dynamic layout simulation [54]		38. Platforms for cloud procurement service [36]	Procurement management informatization (C62)
14. 4D virtual build construction solution optimization [55]		39. Contract informatization management [56]	Contract management informatization (C63)
15. Progress simulation optimization [21]		40. Platform for engineering collaborative management [57]	Informatization of an engineering collaborative management platform (C71)
16. Deformation monitoring informatization [11]	Informatization of construction assembly monitoring (C32)	41. System integration capabilities [36]	
17. Automated monitoring of deep foundation pits and adjacent edges [58]		42. Real-time information collection for collaborative management [5]	Real-time information collection for collaborative management (C72)
18. Intelligent grouting and lifting equipment [59,60]	Construction equipment informatization (C33)	43. Methods of data acquisition [20]	Informatization of data collection methods (C73)
19. Robotic applications such as construction, surveying [24]		44. Automatic data processing [36]	Data processing informatization (C74)
20. Training and education of VR safety [61]	Informatization of personnel security management (C41)	45. Interactivity of hardware and software [47]	Interactivity of hardware and software (C75)
21. Personnel security behavior monitoring [62]		46. Information management for cloud deployment (cloud computing) [36]	Cloud deployment information management (C76)
22. System for determining the real name of laborers [63]	Labor monitoring informatization (C42)		
23. Attendance management [36]			
24. Wage regulation [36]			
25. Statistical analysis of labor force data [36]			

3.3.3. Establishment of an Evaluation Indicator System

The ultimate evaluation outcomes are directly influenced by the selection of evaluation indicators. This study employs a questionnaire survey to ascertain whether the refined 28 key practices can serve as secondary indicators in order to construct the evaluation index system, which uses seven key process areas as primary indicators.

The questionnaire consists of a general description, basic information about the respondents, and scoring the level of significance of the indicators, comments, and suggestions. A five-point Likert scale is utilized to score the significance of indicators [64]. From a total of 150 questionnaires that were distributed through multiple channels including social media platforms, field visits, phone calls, and emails, 142 were successfully recovered of which 131 were valid, with an 87.3% recovery rate for valid questionnaires. The primary causes of invalid questionnaires were respondents' lack of knowledge regarding assembly buildings or well-defined patterns in their responses. The characteristics of the respondents were considered important [65]. A statistical analysis shows that the survey respondents constitute a wide range of fields, including construction units, government departments, design units, scientific research institutions, and institutions of higher education. Approximately 87.03% of the respondents held a bachelor's degree or higher, 48.85% held an intermediate title or higher, and 75.57% had two to four years of work experience or more. This indicates that the respondents possess a substantial amount of expertise and a solid foundation of knowledge to evaluate this questionnaire in a scientific and evidence-based manner. The reliability analysis of the questionnaire showed that the Cronbach's coefficient for the 28 item variables was 0.962, a value significantly greater than 0.7; this indicates that the questionnaire exhibited a satisfactory level of reliability [66]. The examination of the data revealed that the average value of the importance data for each key practice varied between 3.96 and 4.40, reflecting that respondents generally considered the revised key practices that were established through expert interviews as highly significant. The observed standard deviation fell into the range from 0.784 to 0.961, indicating that there was minimal variation in the level of importance of key practices and that the respondents were largely in agreement. Therefore, in this study, all of these 28 key practices were retained as secondary indicators. The final constructed evaluation index system of informatization maturity of assembly building projects is illustrated in Figure 3.

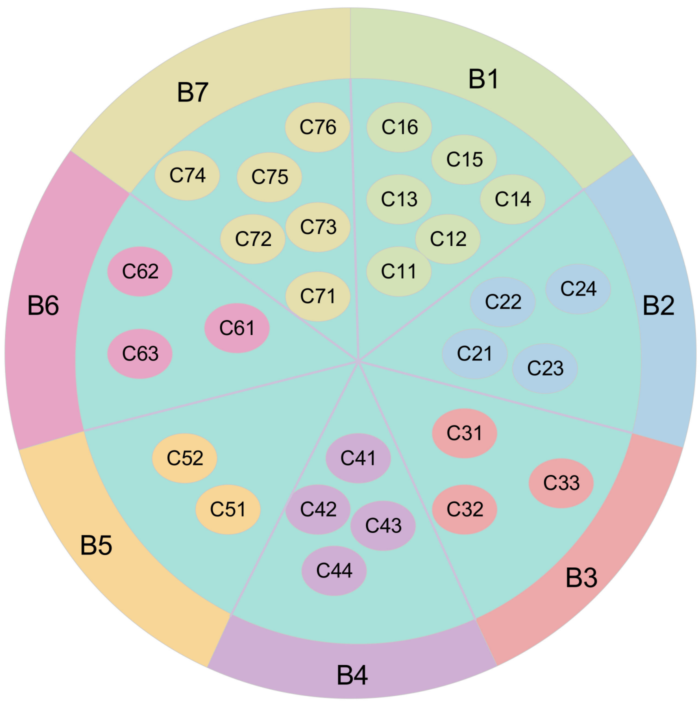

Figure 3. Evaluation indicator system.

3.4. Construction of the Evaluation Model

3.4.1. Determination of Weights

The G1 and entropy weight methods are employed to determine the subjective and objective weights of the informatization maturity evaluation indexes of assembly-building projects [67]. To improve the rationality of weight allocation, linear weighting is employed to ultimately ascertain the comprehensive weight of each indicator.

Step 1: Questionnaires were distributed to seven experts with prior experience in assembly-building projects from construction organizations, government departments, design organizations, research institutes, and higher education institutions (refer to Table 3). The evaluation data from the experts were used to determine the ordinal relationships and relative importance of the evaluation indicators and subjective weights w_j were calculated using the G1 method.

Step 2: Using a five-point Likert scale, experts were requested to assign values to the evaluation indicators and the objective weights u_j of the evaluation indicators were calculated using the entropy weight method.

Step 3: Using the comprehensive weighting method based on linear weighting, the comprehensive weights of the evaluation indexes of the informatization maturity of the assembly building project were obtained by combining the subjective weights w_j and the objective weights u_j as follows:

$$W_j = \alpha w_j + \beta u_j \tag{1}$$

The linearly weighted composite weights can be determined by utilizing the adjustment coefficients α and β associated with the weights. The constraints are established using the distance coefficient function in a way that ensures the distance coefficient is equal to the weight adjustment coefficient. This enables the calculation of the adjustment coefficient values for both the subjective and objective weights. The distance between subjective weight w_j and objective weight u_j is denoted as $d\left(w_j, u_j\right)$. The adjustment coefficients α and β of subjective and objective weights of the evaluation indexes of informatization maturity of assembly-building projects can be calculated using the following formula. α and β were returned to Equation (1) to determine the comprehensive weight value W_j of the evaluation indexes of informatization maturity of assembly-building projects.

$$d\left(w_j, u_j\right)^2 = \sum_{j=1}^{n}\left(w_j - u_j\right)^2 = (\alpha - \beta)^2 \tag{2}$$

where $\alpha + \beta = 1$.

The experts in this step are the same individuals selected to build the indicator system. Table 4 displays the weights assigned to each indicator of the maturity of assembly building informatization, which are computed using the aforementioned methodology.

Table 4. Weight for each indicator.

Level 1 Indicators	G1 Method	Entropy Weight Method	Combined Weigh	Secondary Indicators	G1 Method	Entropy Weight Method	Combined Weigh
B1	0.2145	0.1946	0.2050	C11	0.1072	0.1215	0.1136
				C12	0.1192	0.1485	0.1324
				C13	0.1527	0.2110	0.1789
				C14	0.1721	0.1485	0.1615
				C15	0.2331	0.2219	0.2281
				C16	0.2157	0.1485	0.1855
B2	0.1798	0.1946	0.1869	C21	0.2931	0.1430	0.2420
				C22	0.2261	0.4726	0.3100
				C23	0.2094	0.2414	0.2203
				C24	0.2714	0.1430	0.2277

Table 4. *Cont.*

Level 1 Indicators	G1 Method	Entropy Weight Method	Combined Weigh	Secondary Indicators	G1 Method	Entropy Weight Method	Combined Weigh
B3	0.2088	0.1946	0.2020	C31 C32 C33	0.3041 0.3144 0.3551	0.2879 0.2879 0.4241	0.2967 0.3022 0.3869
B4	0.1072	0.1344	0.1202	C41 C42 C43 C44	0.3168 0.2204 0.1849 0.2779	0.0601 0.3693 0.0759 0.4947	0.2372 0.2666 0.1511 0.3451
B5	0.0762	0.0733	0.0748	C51 C52	0.5000 0.5000	0.6712 0.3288	0.5651 0.4349
B6	0.0845	0.0741	0.0795	C61 C62 C63	0.3418 0.3418 0.3165	0.2426 0.5158 0.2416	0.3031 0.4096 0.2873
B7	0.1291	0.1344	0.1316	C71 C72 C73 C74 C75 C76	0.2343 0.1502 0.1722 0.1296 0.2128 0.1009	0.1938 0.1427 0.1535 0.1535 0.1938 0.1627	0.2157 0.1468 0.1636 0.1406 0.2041 0.1293

3.4.2. Determination of Evaluation Criteria

C11 and C31 are quantitative secondary indicators, while the remaining ones are qualitative. C11 distinguishes maturity levels according to the quantity of relevant BIM technology implementations during the design stage. The classification of the C31 maturity level is determined by the schedule reduction ratio, which is calculated as (schedule completion progress—actual completion progress)/schedule completion progress. Ranking intervals for quantitative indicators were determined by consulting the experts listed in Table 3, as well as an examination of the relevant literature and field research. For qualitative indicators, [0, 100] is divided into four intervals that correspond to the maturity level of informatization of assembly-building projects (refer to Table S2 provided in the Supplementary Materials for the evaluation criteria of qualitative indicators). The average value of these qualitative secondary indicators, as determined by expert scoring, is then used as the evaluation value of the indicator. In order to mitigate the influence of the indicators' attributes on the evaluation, dimensionless standard intervals were utilized, as listed in Table 5.

Table 5. Indicator evaluation criteria interval.

Indicator	Initial Level	Development Level	Normative Level	Continuous Optimization Level
C11	0–3	3–6	6–10	10–15
C31	0–0.05	0.05–0.01	0.01–0.15	0.15–0.3
Qualitative indicator	0–25	25–50	50–75	75–100

3.4.3. Model Building

An evaluation method, known as the cloud matter element theory, integrates cloud modeling with conventional matter element analysis. The essence of this method is to substitute the numerical values assigned to items in the original matter element analysis with the cloud model digital feature expectation (Ex), entropy (En), and super entropy

(He). Then, a comprehensive evaluation of those items is conducted by repurposing the concept of the conventional object meta-analysis. One advantage of employing this method is that it permits the mapping of indicator value uncertainty via the ambiguity present in the cloud model [68]. The formulas and specific steps are illustrated in Figure 4. The upper and lower limits of the standardized interval for the evaluation of the indicators are denoted by a and b, respectively. The value of the constant s may be adjusted in accordance with the level of ambiguity during the grading process. $En\prime$ represents a normal random number generated with Ex being the expected value and He being the standard deviation. The assessment value of the indicator x was determined by averaging the scores of the experts listed in Table 3 on a scale of 0–100.

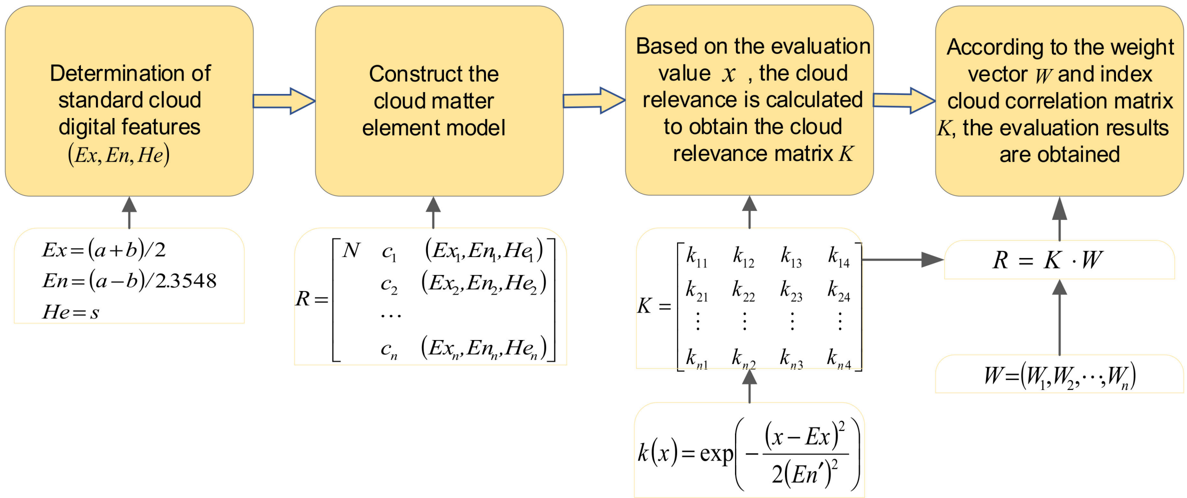

Figure 4. The evaluation process of the cloud matter element mode.

4. Case Study

To validate the evaluation model, the first three-star green public building in Jiangsu Province, China, which has passed the pre-evaluation certification of the 2019 version of the green building standard, with a prefabricated assembly rate of 70%, is selected as a typical case in this study for its analytical and evaluative value.

4.1. Project Overview

The Yangzijiang International Conference Center, situated in Nanjing, Jiangsu Province, China, encompasses a planned site area of 87,000 square meters and a total construction area of approximately 187,200 square meters. Through an examination of the project information and communication with project participants, the technical points of the project's information technology are organized according to the first-level evaluation indicators classified, as detailed in Table 6.

Table 6. The fundamentals of information technology for projects.

Level 1 Indicators	Part of the Informatization Technology Key Points Combing
B1	Model design and analysis; BIM multi-functional applications: including drawing review, pit simulation, material usage statistics, roaming, structural deepening simulation, collision checking, finishing scheme, and low carbon scheme comparison; EVS (earth and environmental sciences 3D visualization) for the analysis and visualization of pits
B2	TEKLA (structural steel detailing) for automated model undercutting; laser scanning to realize point cloud model roof undercutting; and whole process BIM component progress control

Table 6. *Cont.*

Level 1 Indicators	Part of the Informatization Technology Key Points Combing
B3	Multi-sensor structural health inspection; roof structure morphology topology optimization; GIS+inclined photography for earth balance; construction site fabric simulation; and steel structure lifting simulation, quality, and safety inspection
B4	Personnel information management system; QR code personnel management system; WIFI+ safety education subsystem; intelligent AI recognition system (open flame, not wearing helmet, not wearing reflective clothing, crossing the boundary); multi-person VR safety education and experience system; tower hook monitoring system, construction elevator safety monitoring system; unloading platform load early warning system; tower safety monitoring system; and organ master system.
B5	Online surveillance for environmental protection; automatic monitoring of dust reduction linkage and dust spraying; surveillance of noise and nighttime construction violations; and automatic capture of unrinsed vehicles (data access to the regulatory platform)
B6	BIM modeling to compile a formal list to be submitted to commercial procurement
B7	BIM collaboration platform; enterprise cloud storage

4.2. Evaluation Process

The assessment value of quantitative indicators was determined through discussions with project participants, project information, and a PowerPoint presentation on project reporting. Seven experts, as detailed in Table 3, were requested to score the qualitative indicators. The assessment value of the qualitative indicators was then determined by averaging the scores, which are illustrated in Table 7.

Table 7. The assessed value of the indicator.

Secondary Indicators	Assessed Value	Secondary Indicators	Assessed Value	Secondary Indicators	Assessed Value	Secondary Indicators	Assessed Value
C11	14	C22	72	C42	66.9	C63	66.5
C12	84.5	C23	76	C43	51.7	C71	81.8
C13	70.9	C24	85.3	C44	84.4	C72	68.2
C14	71	C31	0.12	C51	91.5	C73	67.9
C15	72	C32	89.5	C52	61.5	C74	73.5
C16	66.5	C33	66.7	C61	69	C75	74.5
C21	71	C41	71.4	C62	66.9	C76	75.5

As an illustration, the standard cloud digital eigenvalue of the second-level index of design informatization is calculated according to Table 5 and Figure 4. The outcomes of this calculation are presented in Table 8.

Table 8. The standard cloud digital eigenvalue of the second-level index of design informatization.

Serial Number	Initial Level (Ex, En, He)	Development Level (Ex, En, He)	Normative Level (Ex, En, He)	Continuous Optimization Level (Ex, En, He)
C11	(1.5, 1.274, 0.1)	(4.5, 1.274, 0.1)	(8.0, 1.699, 0.1)	(12.5, 2.123, 0.1)
C12	(12.5, 10.617, 0.5)	(37.5, 10.617, 0.5)	(62.5, 10.617, 0.5)	(87.5, 10.617, 0.5)
C13	(12.5, 10.617, 0.5)	(37.5, 10.617, 0.5)	(62.5, 10.617, 0.5)	(87.5, 10.617, 0.5)
C14	(12.5, 10.617, 0.5)	(37.5, 10.617, 0.5)	(62.5, 10.617, 0.5)	(87.5, 10.617, 0.5)
C15	(12.5, 10.617, 0.5)	(37.5, 10.617, 0.5)	(62.5, 10.617, 0.5)	(87.5, 10.617, 0.5)
C16	(12.5, 10.617, 0.5)	(37.5, 10.617, 0.5)	(62.5, 10.617, 0.5)	(87.5, 10.617, 0.5)

According to Table 8 and Figure 4, the correlation between design informatization level 2 indicators and the standard cloud of each maturity level is calculated, with the results presented in Table 9.

Table 9. The correlation between design informatization level 2 indicators and the standard cloud of each maturity level.

Serial Number	Initial Level	Development Level	Normative Level	Continuous Optimization Level
C11	0.0000	0.0000	0.0020	0.7792
C12	0.0000	0.0001	0.1124	0.9658
C13	0.0000	0.0070	0.7316	0.2948
C14	0.0000	0.0069	0.7259	0.2988
C15	0.0000	0.0052	0.6703	0.3439
C16	0.0000	0.0240	0.9314	0.1416

The cloud correlation matrix for design informatization is constructed using the correlation between design informatization level 2 indicators and the normal cloud of each maturity level standard as follows:

$$K_{B1} = \begin{bmatrix} 0.0000 & 0.0000 & 0.0020 & 0.7792 \\ 0.0000 & 0.0001 & 0.1124 & 0.9658 \\ 0.0000 & 0.0070 & 0.7316 & 0.2948 \\ 0.0000 & 0.0069 & 0.7259 & 0.2988 \\ 0.0000 & 0.0052 & 0.6703 & 0.3439 \\ 0.0000 & 0.0240 & 0.9314 & 0.1416 \end{bmatrix}$$

The weights of the secondary indicators of design informatization are represented by the vector shown below.

$$W_{B1} = (0.1136,\ 0.1324,\ 0.1789,\ 0.1615,\ 0.2881,\ 0.1855)$$

The cloud correlation of design informatization to each maturity level is determined according to Figure 4:

$$R_{B1} = (0.0000,\ 0.0080,\ 0.5889,\ 0.4221)$$

Similarly, the cloud correlation of production and transportation informatization, construction and assembly informatization, personnel, material and machine management informatization, environmental management information, business management informatization, and engineering collaborative management informatization for each maturity level can be obtained as follows:

$$\begin{aligned} R_{B2} &= (0.0000, 0.0036, 0.5044, 0.5242) \\ R_{B3} &= (0.0000, 0.0386, 0.6580, 0.4311) \\ R_{B4} &= (0.0002, 0.0689, 0.5193, 0.4598) \\ R_{B5} &= (0.0000, 0.0034, 0.4464, 0.5480) \\ R_{B6} &= (0.0076, 0.3771, 0.5884, 0.1072) \\ R_{B7} &= (0.0000, 0.0061, 0.5634, 0.4685) \end{aligned}$$

The cloud correlation matrix for the integrated evaluation of the target layer is constructed using the first-level indicator cloud correlation as follows:

$$K = \begin{bmatrix} 0.0000 & 0.0080 & 0.5889 & 0.4221 \\ 0.0000 & 0.0036 & 0.5044 & 0.5242 \\ 0.0000 & 0.0386 & 0.6580 & 0.4311 \\ 0.0002 & 0.0689 & 0.5193 & 0.4598 \\ 0.0000 & 0.0034 & 0.4464 & 0.5480 \\ 0.0076 & 0.3771 & 0.5884 & 0.1072 \\ 0.0000 & 0.0061 & 0.5634 & 0.4685 \end{bmatrix}$$

The vector of weights for the level 1 indicators is

$$W = (0.2050, 0.1869, 0.2020, 0.1202, 0.0748, 0.0795, 0.1316)$$

The comprehensive evaluation of the project's informatization maturity of the project yielded the following result: $R = (0.0006, 0.0494, 0.5646, 0.4380)$. According to the principle of maximum affiliation, the comprehensive informatization maturity level of the Yangzi River International Conference Center project is considered to be a normative level, which is consistent with the degree of informatization of the project.

5. Results and Discussion

According to the previous analysis, the comprehensive informatization maturity level of the project is considered to be a normative level. The evaluation outcomes of production and transportation informatization and environmental management information demonstrate a level of continuous optimization, with weights of 0.1869 and 0.0748, respectively. With respective weights of 0.2050, 0.2020, 0.1202, 0.0795, and 0.1316, the evaluation outcomes of design informatization, construction assembly informatization, man-material-machine management informatization, business management informatization, and engineering collaborative management informatization are all at the normative level. Therefore, implementation should prioritize informatization in the following areas: design, construction assembly informatization, man-material-machine management informatization, business management informatization, and project collaboration management informatization.

5.1. Design Informatization

The case study evaluated the degree of BIM design performance application and BIM co-design for this project at a continuous optimization level. It was found that this project is an EPC general contracting undertaking and jointly led by the constructor and designer such that it possesses a wide range of innovative BIM applications and a high degree of co-design. Furthermore, it incorporated a substantial number of design specialties. Therefore, this project provides a valuable reference for other undertakings. The standardized design of components is evaluated at a normative level, given the limited level of normative in assembly building design at present and the inability of the design to meet the standards of industrialized buildings [69]. As there is currently no unified standard for the Industry Foundation Class (IFC), instances of missing or incomplete data may arise during the data exchange of various software applications [47]. Therefore, the project's BIM software interactivity received a rating of normative level. The maturity of prefabricated component disassembly design and BIM modeling accuracy are also rated at the normative level, which failed to reach the continuous optimization level. This indicates that the informatization of assembly building design has the potential for further development, particularly with regard to the standardized design of components and the IFC standard.

The efficiency of collaborative design for assembly-building projects involving multiple fields of expertise is impacted by BIM software data interactivity (0.2281), which carries the most weight in design informatization. Therefore, it is critical to adopt intermediary formats such as IFC and promote standardized BIM data interaction [70]. It enables effective collaboration and communication of design information throughout the duration of the project. Although their individual weightings are relatively low, component standardized design (0.1855), prefabricated component split design (0.1789), and BIM modeling accuracy (0.1615) collectively contribute to the achievement of streamlined, precise, and controllable design processes. Design consistency and construction efficiency are improved by the standardized design of components [49]. In order to improve the quality and stability of components, the prefabricated component split design takes into account transportation and installation constraints [41], while BIM modeling accuracy enhances design precision by ensuring that the design model reflects the actual situation. Although assigned the lowest weights (0.1136 and 0.1324, respectively), the degree of application of BIM design performance and BIM collaborative design continue to exert an influence on the informatization of assembly-building projects. Therefore, it is important to focus on BIM software data interactivity during the development of informatization for assembly-building projects.

5.2. Production and Transportation Informatization

Information on production and transportation comprises the following: informatization of production equipment, component production scheduling informatization, informatization of the component transportation program, and informatization of component traceability. Informatization of the production equipment and component production scheduling informatization of the case are evaluated at the normative level. Informatization of the component transportation program and informatization of component traceability are evaluated at the level of continuous optimization. This demonstrates that further improvements are required in the informatization of production and transportation in order to reduce the costs associated with producing and transporting assembly components and prevent a significant increase in the cost of assembled buildings. This can be achieved by enhancing the automation of component production, optimizing the production plan, and real-time tracking and monitoring of dynamic information during component transportation.

The component production scheduling informatization (0.3100) carries the most weight. Informatization scheduling enables the formulation and optimization of production plans, which substantially increases production efficiency by reducing waiting time, cross work, and waste [71]. Although the weights assigned to the informatization of production equipment (0.2420), informatization of component transportation program (0.2203), and informatization of component traceability (0.2203) are relatively low, their impacts on the overall informatization and construction efficiency of the project remain significant. By monitoring and remotely controlling the production equipment in real-time, planning the optimal transportation scheme using logistics information system and real-time tracking technology, and applying digital marking, RFID technology, and information management system to ensure the unique identification and full life cycle traceability of the components, the project can achieve a more efficient, controllable, and traceable production and transportation process.

5.3. Construction Assembly Informatization

The project used sensor-based monitoring of critical structural nodes and additional technologies to effectively monitor the quality of assembly and informatization of the construction assembly monitoring was assessed at the continuous optimization level. Nonetheless, the informatization in construction assembly planning and construction equipment was evaluated at a normative level, failing to reach the level of continuous optimization. Evidently, advancements in construction assembly informatization remain attainable; therefore, it is imperative to develop an optimization model for project scheduling that is both user-friendly and intuitive and to implement more sophisticated construction equipment.

The highest weight in construction assembly informatization is construction equipment informatization (0.3869), followed by informatization of construction assembly monitoring (0.3022), and finally construction assembly planning informatization (0.2976). In addition to enhancing productivity, quality, and safety, intelligent equipment can alleviate the workload of construction personnel. For example, robotic automated assembly technology will improve the efficiency, quality, and safety of assembled buildings [72]. Despite construction assembly planning informatization carrying the least amount of weight, precise planning is critical to facilitate a smooth assembly process [73].

5.4. Informatization of Personnel, Material, and Machine Management

The level of continuous optimization was assigned to the project's informatization of machinery and equipment safety monitoring and the normative level was assigned to the information for managing personnel safety, workers, and material supervision informatization. The project utilizes IoT technology and a remote monitoring system to monitor the operational status of equipment in real-time, which is worth learning from other projects. To ensure the seamless on-time completion and controllable quality of the assembly construction project, however, it is still necessary to increase the input of information technology in personnel and materials and to realize the integration of personnel, materials, and machinery information management [74].

Informatization of personnel, material, and machinery management includes personnel safety management, labor monitoring, material supervision, and machinery and equipment safety monitoring, with weights of 0.2372, 0.2666, 0.1511, and 0.3451, respectively. In assembled construction, the safety of heavy equipment is crucial as it affects the overall safety of the project and its personnel. Monitoring equipment status and performance through informatization can effectively mitigate equipment failures, enhance reliability and service life, and guarantee uninterrupted production. In assembly-building projects, the traditional way of material supervision is still dominant and the application of information technology has not been popularized yet [40]. Subsequent efforts should therefore promote the integration of information technology into material supervision and innovate the method of material supervision. Personnel safety management and labor monitoring are relatively comparable in terms of weight, which are important components of the informatization of assembly construction projects. On-site environments in the construction industry are complex and dangerous and involve higher operating risks than those in other industries [75]. Therefore, it is very important to strengthen personnel safety management and labor monitoring. To this end, we can use the large data systems architecture based on artificial intelligence for engineering personnel safety management, enriching and improving construction safety of personnel management concepts and technical means [76].

5.5. Environmental Management Informatization

Due to the direct connection between the project's environmental data and the local smart site supervision platform, the environmental monitoring informatization is rated at the continuous optimization level in terms of model application. However, the oversight of construction waste lacks a comprehensive visualization supervision system for the entire process; it is thus rated at the normative level. At present, environmental problems are becoming increasingly serious, especially climate change [77]. This has aroused the concern of governments and environmental organizations, which have successively put forward sustainable development strategies. Therefore, energy-saving technologies and carbon emission reduction technologies are widely used in assembly-building projects [2]. However, there is still significant room for advancement in the informatization of construction waste supervision.

The environmental monitoring informatization (0.5651) and construction waste supervision informatization (0.4349) share a relatively equal weight in environmental management informatization, indicating that assembly-building projects place a comprehensive emphasis on environmental protection and sustainable development. However, on-site construction environmental monitoring is often conducted in a manual and random manner [78]. Such approaches are unable to monitor ongoing on-site environmental changes. Hong collected empirical data on noise, vibration, and dust on a construction site through several IoT sensors [79], which help manage the construction site environment. Therefore, it is necessary to use information technology to assess the level of construction pollutants emitted by on-site construction equipment and activities.

5.6. Business Management Informatization

Business management informatization is realized through the informatization of procurement management, contract management, and cost management. Based on actual instances, the level of informatization in cost management and contract management is considered normative, whereas informatization in procurement management is regarded at the developmental level. Due to the absence of an ideal e-commerce procurement system and online supply chain, the project finds it challenging to monitor the procurement process [80]. Future work should focus on bridging the gap of procurement management informatization in order to reduce the impact of procurement on schedule and cost, shorten the construction period, and reduce the cost.

With information asymmetry in the procurement process potentially causing project delays or cost overruns, procurement management informatization (0.4096) has the highest weight [81]. The project's informatization maturity is impacted by the equally significant cost management informatization (0.3031) and contract management informatization (0.2873). With the appropriate software and technology, it is possible to reduce cost uncertainty and improve contract management at the beginning of the project, increase information transparency, and ultimately improve business management informatization.

5.7. Engineering Collaborative Management Informatization

The project incorporates a BIM collaborative work platform, which provides classification management and preview and download functions of data. As a result, the engineering collaborative management platform and cloud deployment information management are rated at the continuous optimization level. However, there is still a certain failure rate in the data collection, transmission, and calculation of its hardware and software interaction. Consequently, collaborative management information collection in real-time, the informatization for data collection methods and data processing, and the interactivity of hardware and software are rated at a normative level. Therefore, it is essential to enhance the adaptability and further strengthen the data acquisition and transmission capabilities of the collaborative management platform [82].

Of the engineering collaborative management informatization elements, informatization of an engineering collaborative management platform holds the highest weight (0.2157), which improves engineering management efficiency, reduces project execution costs, guarantees that projects are completed on schedule, and fosters teamwork and communication [83]. The second highest weight is attributed to the interactivity of hardware and software (0.2041), following the informatization of an engineering collaborative management platform. Excellent hardware and software interactivity facilitates accurate data support and user-friendly experiences, thereby enhancing decision-making support and fostering collaborative work efficiency. The weight of collaborative management information collection in real-time (0.1468), informatization of data collection methods (0.1636), data processing informatization (0.1406), and cloud deployment information management (0.1293) are relatively balanced. They affect the information level of prefabricated building projects. Sophisticated artificial intelligence technologies, algorithms, and data processing tools can capture project data in real-time and analyze and process it. This enables a better response to changes and decision making. In terms of data reliability and security, data can be centrally managed, shared, and backed up through cloud deployment information management.

6. Conclusions

As the construction industry shifts toward greener and lower-carbon practices, the construction industry is beginning to use information technology to improve productivity and reduce pollution. Assembly building is the trend of future development in the construction industry. In order to improve the maturity of informatization of assembly-building projects and promote their sustainable development, it is critical to build a corresponding evaluation system. The findings presented in this paper are as follows:

(1) An evaluation index system for the informatization maturity of assembly-building projects is established. Utilizing the capability maturity model as a foundation, this research strives to establish the level of informatization maturity of assembly-building projects. Through a literature review and utilization of expert interviews and questionnaire surveys, this study finalizes an evaluation system comprising seven level 1 rating indicators and 28 rating level 2 indicators;

(2) An evaluation model is developed for assessing the informatization maturity in assembly-building projects. Utilizing a comprehensive assignment method based on the ordinal relationship method and entropy weight method, the weight of each index is determined. Subsequently, the evaluation criteria for the maturity of informatization in assembly-building projects are formulated via examination of relevant standards and expert discussions. In conclusion, the evaluation model for the informatization maturity in assembly-building projects is developed using the evaluation criteria and the cloud matter element theory;

(3) The Yangzijiang International Conference Center project is chosen for empirical investigation. The information maturity of this assembly building project is evaluated by applying the previously established index system and evaluation model. The comprehensive informatization maturity grade is of normative level and the evaluation outcomes align with the project's actual operations, thereby validating the feasibility and effectiveness of the model.

In conclusion, this paper provides instances to demonstrate that the assessment of the maturity of informatization in assembly-building projects based on the CMM-CME methodology is scientific and reasonable. By converting the subjective evaluation into numerical values that can be analyzed, this method enables a more precise determination of the level of informatization maturity in assembly-building projects and enables the monitoring of the maturity of the second-level indexes. Furthermore, it establishes a scientific foundation for the management of informatization management in such projects.

Despite successfully achieving the intended research objectives, this paper bears a few limitations. To begin with, the validation of the evaluations is based on a single case, which may not be particularly representative; subsequent studies may be conducted with various cases in consideration for the purpose of comparison and analysis. Second, the evaluation index system developed in this paper comprises a significant portion of the qualitative indexes and the evaluation of the indexes relies on the personal experience of the experts, which introduces a degree of subjectivity. Therefore, future research will employ industry big data to convert qualitative indicators into quantitative ones, to enhance the objectivity of the evaluation.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/buildings14040918/s1, Table S1: Initial screening of key practices; Table S2: Evaluation criteria for qualitative indicators.

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References

1. Zhou, Y.; Wei, X.; Peng, Y.; Lv, Z. The Modelling of Digital Twins Technology in the Construction Process of Prefabricated Buildings. *Adv. Civ. Eng.* **2021**, *2021*, 2801557. [CrossRef]
2. Liu, S.; Li, Z.; Teng, Y.; Dai, L. A dynamic simulation study on the sustainability of prefabricated buildings. *Sustain. Cities Soc.* **2022**, *77*, 103551. [CrossRef]
3. Li, N.; Fan, Z.; Liu, X. Impact Evaluation of Prefabricated Buildings Cost on Game Theory-Cloud Model. *J. Math.* **2022**, *2022*, 3635009. [CrossRef]
4. Li, R.Y.M.; Li, B.; Zhu, X.; Zhao, J.; Pu, R.; Song, L. Modularity clustering of economic development and ESG attributes in prefabricated building research. *Front. Environ. Sci.* **2022**, *10*, 977887. [CrossRef]
5. Chen, K.; Xu, G.; Xue, F.; Zhong, R.Y.; Liu, D.; Lu, W. A Physical Internet-enabled Building Information Modelling System for prefabricated construction. *Int. J. Comput. Integr. Manuf.* **2017**, *31*, 349–361. [CrossRef]
6. Wu, F.; Liu, X.; Wang, Y.; Li, X.; Zhou, M.; Su, J. Research on Evaluation Model of Hospital Informatization Level Based on Decision Tree Algorithm. *Secur. Commun. Netw.* **2022**, *2022*, 3777474. [CrossRef]
7. Yao, F.; Ji, Y.; Li, H.X.; Liu, G.; Tong, W.; Liu, Y.; Wang, X. Evaluation of Informatization Performance of Construction Industrialization EPC Enterprises in China. *Adv. Civ. Eng.* **2020**, *2020*, 1314586. [CrossRef]
8. Zhang, H.; Zhang, X.; Gu, F. Research on the Construction of Logistics Informatization Evaluation System for Large State-owned Energy Enterprises. *IOP Conf. Ser. Mater. Sci. Eng.* **2019**, *612*, 042041. [CrossRef]
9. Poghosyan, A.; Manu, P.; Mahamadu, A.-M.; Akinade, O.; Mahdjoubi, L.; Gibb, A.; Behm, M. A web-based design for occupational safety and health capability maturity indicator. *Saf. Sci.* **2020**, *122*, 104516. [CrossRef]
10. Hao, L.; Su, J. Optimal Allocation of Human Resource Structure Based on Capability Maturity Model Integration. *Secur. Commun. Netw.* **2022**, *2022*, 3162328. [CrossRef]
11. Zhao, P.; Liu, X.; Liang, Z.; Sun, L. Destruction Feature Extraction of Prefabricated Residential Building Components Based on BIM. *Sci. Program.* **2022**, *2022*, 5798625. [CrossRef]
12. Xu, J.; Zhang, Q.; Teng, Y.; Pan, W. Integrating IoT and BIM for tracking and visualising embodied carbon of prefabricated buildings. *Build. Environ.* **2023**, *242*, 110492. [CrossRef]
13. Wu, S.; Liu, Q. Analysis on the Application of BIM and RFID in Life Cycle Management of Prefabricated Building. *IOP Conf. Ser. Mater. Sci. Eng.* **2020**, *780*, 032012. [CrossRef]
14. Volpe, S.; Sangiorgio, V.; Petrella, A.; Coppola, A.; Notarnicola, M.; Fiorito, F. Building Envelope Prefabricated with 3D Printing Technology. *Sustainability* **2021**, *13*, 8923. [CrossRef]
15. Wang, Z.; Liu, C.; Song, B.; Lv, Z. Panoramic Display and Planning Simulation of Civil Engineering Project Based on Virtual Reality Technology. *Complexity* **2020**, *2020*, 1424757. [CrossRef]
16. Gao, Y.; Wang, J.; Yiu, T.W. Multi-information integration-based life cycle analysis of greenhouse gas emissions for prefabricated construction: A case study of Shenzhen. *Environ. Impact Assess. Rev.* **2024**, *104*, 107330. [CrossRef]
17. Asgari, Z.; Rahimian, F.P. Advanced Virtual Reality Applications and Intelligent Agents for Construction Process Optimisation and Defect Prevention. *Procedia Eng.* **2017**, *196*, 1130–1137. [CrossRef]
18. Xu, Z.; Wang, X.; Rao, Z. Automated Optimization for the Production Scheduling of Prefabricated Elements Based on the Genetic Algorithm and IFC Object Segmentation. *Processes* **2020**, *8*, 1593. [CrossRef]
19. Valinejadshoubi, M.; Bagchi, A.; Moselhi, O. Damage detection for prefabricated building modules during transportation. *Autom. Constr.* **2022**, *142*, 104466. [CrossRef]
20. Xu, Z.; Liang, Y.; Lu, H.; Kong, W.; Wu, G. An approach for monitoring prefabricated building construction based on feature extraction and point cloud segmentation. *Eng. Constr. Archit. Manag.* **2022**, *30*, 5302–5332. [CrossRef]
21. Yan, X.; Zhang, H.; Zhang, W. Intelligent monitoring and evaluation for the prefabricated construction schedule. *Comput. Aided Civil Infrastruct. Eng.* **2022**, *38*, 391–407. [CrossRef]
22. Shen, Y.; Xu, M.; Lin, Y.; Cui, C.; Shi, X.; Liu, Y. Safety Risk Management of Prefabricated Building Construction Based on Ontology Technology in the BIM Environment. *Buildings* **2022**, *12*, 765. [CrossRef]
23. Yang, B.; Dong, M.; Wang, C.; Liu, B.; Wang, Z.; Zhang, B. IFC-Based 4D Construction Management Information Model of Prefabricated Buildings and Its Application in Graph Database. *Appl. Sci.* **2021**, *11*, 7270. [CrossRef]
24. Zhou, T.; Zhu, Q.; Du, J. Intuitive robot teleoperation for civil engineering operations with virtual reality and deep learning scene reconstruction. *Adv. Eng. Inform.* **2020**, *46*, 101170. [CrossRef]
25. Manzoni, L.V.; Price, R.T. Identifying extensions required by RUP (Rational Unified Process) to comply with CMM (Capability Maturity Model) levels 2 and 3. *IEEE Trans. Softw. Eng.* **2003**, *29*, 181–192. [CrossRef]
26. Gökalp, E.; Martinez, V. Digital transformation maturity assessment: Development of the digital transformation capability maturity model. *Int. J. Prod. Res.* **2021**, *60*, 6282–6302. [CrossRef]

27. Wang, Y.; Chen, H.; Tiong, R.L.K. An exploratory research on the maturity level of public's emergency capability. *Nat. Hazards* **2023**, *119*, 325–355. [CrossRef]
28. Liao, R.; Chen, H.; Sun, C.; Sun, Y. An Exploratory Study on Two-Dimensional Project Management Maturity Model. *EMJ Eng. Manag. J.* **2022**, *35*, 445–459. [CrossRef]
29. Shen, L.; Du, X.; Cheng, G.; Wei, X. Capability Maturity Model (CMM) method for assessing the performance of low-carbon city practice. *Environ. Impact Assess. Rev.* **2021**, *87*, 106549. [CrossRef]
30. Lu, W.; Chen, K.; Zetkulic, A.; Liang, C. Measuring building information modeling maturity: A Hong Kong case study. *Int. J. Constr. Manag.* **2018**, *21*, 299–311. [CrossRef]
31. Sun, C.; Xu, H.; Wan, D.; Li, Y.; Vignali, V. Building Information Modeling Application Maturity Model (BIM-AMM) from the Viewpoint of Construction Project. *Adv. Civ. Eng.* **2021**, *2021*, 6684031. [CrossRef]
32. Luan, H.; Li, L.; Jiang, P.; Zhou, J. Critical Factors Affecting the Promotion of Emerging Information Technology in Prefabricated Building Projects: A Hybrid Evaluation Model. *Buildings* **2022**, *12*, 1577. [CrossRef]
33. Wei, J.; Chen, H.; Long, R.; Zhao, F. Application of the capability maturity model to evaluating the carbon capability maturity of urban residents in 10 Eastern provinces of China. *Resour. Conserv. Recycl.* **2019**, *148*, 11–22. [CrossRef]
34. Liu, J.; Gong, E.; Wang, D.; Teng, Y. Cloud Model-Based Safety Performance Evaluation of Prefabricated Building Project in China. *Wirel. Pers. Commun.* **2018**, *102*, 3021–3039. [CrossRef]
35. Liang, H.; Zhang, S.; Su, Y. Evaluating the Efficiency of Industrialization Process in Prefabricated Residential Buildings Using a Fuzzy Multicriteria Decision-Making Method. *Math. Probl. Eng.* **2017**, *2017*, 6078490. [CrossRef]
36. *10 New Technologies in the Construction Industry*, 2017th ed. Ministry of Housing and Urban-Rural Development of the People's Republic of China: Beijing, China, 2017.
37. Maurer, C.; Sprenger, W.; Franz, S.; Boudhaim, M.; Lodewijks, J.; Rüppel, U.; Kuhn, T.E. Machine-code functions in BIM for cost-effective high-quality buildings. *Energy Build.* **2017**, *155*, 467–474. [CrossRef]
38. Jusoh, Z.M.; Kasim, N.; Ibrahim, M.U.; Sarpin, N.; Noh, H.M.; Zainal, R. Influential Factors for Effective Materials Management in Construction Projects. *Int. J. Sustain. Constr. Eng Technol.* **2018**, *9*, 45–55. [CrossRef]
39. Wang, J.; Shen, Y.; Xiong, X.; Wang, X.; Fang, X. Research on multi-person collaborative design of BIM drawing based on blockchain. *Sci. Rep.* **2022**, *12*, 16312. [CrossRef] [PubMed]
40. Wu, X. Wireless management system of prefabricated construction materials based on BIM technology. *EURASIP J. Wirel. Commun. Netw.* **2021**, *2021*, 116. [CrossRef]
41. Su, M.; Yang, B.; Wang, X.; Chen, Q. Research on Integrated Design of Modular Steel Structure Container Buildings Based on BIM. *Adv. Civ. Eng.* **2022**, *2022*, 4574676. [CrossRef]
42. Zhu, Z.; Ren, X.; Chen, Z. Integrated detection and tracking of workforce and equipment from construction jobsite videos. *Autom. Constr.* **2017**, *81*, 161–171. [CrossRef]
43. Guo, Z.; Gao, S.; Liu, J. Application of BIM Technology in Prefabricated Buildings. *IOP Conf. Ser. Earth Environ. Sci.* **2017**, *81*, 012139. [CrossRef]
44. Yang, J.; Lee, D.; Baek, C.; Park, C.; Lan, B.Q.; Lee, D. Leveraging Blockchain for Scaffolding Work Management in Construction. *IEEE Access* **2022**, *10*, 39220–39238. [CrossRef]
45. Hong, J.; Kang, H.; Hong, T.; Park, H.S.; Lee, D.-E. Development of a prediction model for the proportion of buildings exposed to construction noise in excess of the construction noise regulation at urban construction sites. *Autom. Constr.* **2021**, *125*, 103656. [CrossRef]
46. Smaoui, N.; Kim, K.; Gnawali, O.; Lee, Y.-J.; Suh, W. Respirable Dust Monitoring in Construction Sites and Visualization in Building Information Modeling Using Real-time Sensor Data. *Sens. Mater.* **2018**, *30*, 1775. [CrossRef]
47. An, Y.; Lin, X.; Li, H.; Wang, Y. Sandpile-simulation-based graph data model for MVD generative design of shield tunnel lining using information entropy. *Adv. Eng. Inform.* **2023**, *57*, 102108. [CrossRef]
48. Guan, S.; Wang, J.; Wang, X.; Zhang, B.; Liang, H. Improved RefineDNet algorithm for precise environmental perception of autonomous earthmoving machinery under haze and fugitive dust conditions. *Adv. Eng. Inform.* **2024**, *59*, 102326. [CrossRef]
49. Kang, J.; Dong, W.; Huang, Y. A Bim-Based Automatic Design Optimization Method for Modular Steel Structures: Rectangular Modules as an Example. *Buildings* **2023**, *13*, 1410. [CrossRef]
50. Zhou, F.; Chen, Y. Research and Design of MES System for Intelligent Production Line of Prefabricated Building Components. *J. Phys. Conf. Ser.* **2021**, *2029*, 012048. [CrossRef]
51. Liu, D.; Li, X.; Chen, J.; Jin, R. Real-Time Optimization of Precast Concrete Component Transportation and Storage. *Adv. Civ. Eng.* **2020**, *2020*, 012048. [CrossRef]
52. Ma, G.; Jiang, J.; Shang, S. Visualization of Component Status Information of Prefabricated Concrete Building Based on Building Information Modeling and Radio Frequency Identification: A Case Study in China. *Adv. Civ. Eng.* **2019**, *2019*, 6870507. [CrossRef]
53. Urazova, N.G.; Kotelnikov, N.V.; Oparina, T.A.; Malanova, A.A. Effectiveness of using visualization technologies in construction. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *751*, 012085. [CrossRef]
54. Schwabe, K.; Teizer, J.; König, M. Applying rule-based model-checking to construction site layout planning tasks. *Autom. Constr.* **2019**, *97*, 205–219. [CrossRef]

55. Ivson, P.; Nascimento, D.; Celes, W.; Barbosa, S.D. CasCADe: A Novel 4D Visualization System for Virtual Construction Planning. *IEEE Trans. Vis. Comput. Graph.* **2018**, *24*, 687–697. [CrossRef] [PubMed]
56. Park, S.H.; Kim, Y.S. An Assessment of Contract Management Capabilities for Overseas Construction Projects. *KSCE J. Civ. Eng.* **2017**, *22*, 2147–2158. [CrossRef]
57. Wang, Y.p. Research on the Application of Feature Modeling of Prefabricated Building Components Based on BIM. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *676*, 012047. [CrossRef]
58. Li, Z.; Cao, R. Displacement Monitoring during the Excavation and Support of Deep Foundation Pit in Complex Environment. *Adv. Civ. Eng.* **2021**, *2021*, 5715306. [CrossRef]
59. Ji, Y.; Zhao, Z.; Yao, F.; Li, H.X.; Li, Y.; Du, X.; Foong, L. Factors Influencing Sleeve Grouting Quality for Prefabricated Building: An Interpretive Structural Modeling Approach. *Adv. Civ. Eng.* **2021**, *2021*, 5598424. [CrossRef]
60. Liu, Z.-S.; Meng, X.-T.; Xing, Z.-Z.; Cao, C.-F.; Jiao, Y.-Y.; Li, A.-X. Digital Twin-Based Intelligent Safety Risks Prediction of Prefabricated Construction Hoisting. *Sustainability* **2022**, *14*, 5179. [CrossRef]
61. Man, S.S.; Wen, H.; So, B.C.L. Are virtual reality applications effective for construction safety training and education? A systematic review and meta-analysis. *J. Saf. Res.* **2023**, *88*, 230–243. [CrossRef]
62. Wu, H.; Zhao, J. An intelligent vision-based approach for helmet identification for work safety. *Comput. Ind.* **2018**, *100*, 267–277. [CrossRef]
63. Ragnoli, M.; Colaiuda, D.; Leoni, A.; Ferri, G.; Barile, G.; Rotilio, M.; Laurini, E.; De Berardinis, P.; Stornelli, V. A LoRaWAN Multi-Technological Architecture for Construction Site Monitoring. *Sensors* **2022**, *22*, 8685. [CrossRef] [PubMed]
64. Bancsik, K.; Ilea, C.D.N.; Daina, M.D.; Bancsik, R.; Șuteu, C.L.; Bîrsan, S.D.; Manole, F.; Daina, L.G. Comparative Analysis of Patient Satisfaction Surveys—A Crucial Role in Raising the Standard of Healthcare Services. *Healthcare* **2023**, *11*, 2878. [CrossRef] [PubMed]
65. Carvalho, J.V.; Rocha, Á.; van de Wetering, R.; Abreu, A. A Maturity model for hospital information systems. *J. Bus. Res.* **2019**, *94*, 388–399. [CrossRef]
66. Deng, S.; Zhu, H.; Peng, R.; Pan, Y. Development and validation of a cognitive model-based novel questionnaire for measuring potential unsafe behaviors of construction workers. *Int. J. Occup. Saf. Ergon.* **2021**, *28*, 2566–2573. [CrossRef]
67. Zhao, Z.; Liu, J. Analysis of Museum Cultural Creation from the Perspective of Cultural Industry. *Sci. Program.* **2022**, *2022*, 8138574. [CrossRef]
68. Wang, Y.; Zhang, X.e.; Wu, Y. Eutrophication Assessment Based on the Cloud Matter Element Model. *Int. J. Environ. Res. Public Health* **2020**, *17*, 334. [CrossRef] [PubMed]
69. Li, N.; Feng, Y.; Liu, J.; Ye, X.; Xie, X. Research on the Modular Design and Application of Prefabricated Components Based on KBE. *Buildings* **2023**, *13*, 2980. [CrossRef]
70. Krijnen, T.; Beetz, J. An IFC schema extension and binary serialization format to efficiently integrate point cloud data into building models. *Adv. Eng. Inform.* **2017**, *33*, 473–490. [CrossRef]
71. Chang, C.; Han, M.; Bigaud, D. Production Scheduling Optimization of Prefabricated Building Components Based on DDE Algorithm. *Math. Probl. Eng.* **2021**, *2021*, 6672753. [CrossRef]
72. Zhu, A.Y.; Dai, T.H.; Xu, G.Y.; Pauwels, P.; de Vries, B.; Fang, M. Deep Reinforcement Learning for Real-Time Assembly Planning in Robot-Based Prefabricated Construction. *IEEE Trans. Autom. Sci. Eng.* **2023**, *20*, 1515–1526. [CrossRef]
73. Cuellar Lobo, J.D.; Lei, Z.; Liu, H.; Li, H.X.; Han, S.; Shafigh, P. Building Information Modelling- (BIM-) Based Generative Design for Drywall Installation Planning in Prefabricated Construction. *Adv. Civ. Eng.* **2021**, *2021*, 6638236. [CrossRef]
74. Feiyu, C.; Yisheng, L. Evaluation of risk for construction safety of fabricated buildings based on analytic hierarchy process. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *791*, 012063. [CrossRef]
75. Huang, Y.-H.; Sung, C.-Y.; Chen, W.T.; Liu, S.-S. Relationships between Social Support, Social Status Perception, Social Identity, Work Stress, and Safety Behavior of Construction Site Management Personnel. *Sustainability* **2021**, *13*, 3184. [CrossRef]
76. Yi, X.; Wu, J. Research on Safety Management of Construction Engineering Personnel under "Big Data + Artificial Intelligence". *OJBM* **2020**, *08*, 1059–1075. [CrossRef]
77. Feng, L.; Hu, P.; Wang, H.; Chen, M.-m.; Han, J. Improving City Water Quality through Pollution Reduction with Urban Floodgate Infrastructure and Design Solutions: A Case Study in Wuxi, China. *Int. J. Environ. Res. Public Health* **2022**, *19*, 10976. [CrossRef] [PubMed]
78. Zhong, B.; Guo, J.; Zhang, L.; Wu, H.; Li, H.; Wang, Y. A blockchain-based framework for on-site construction environmental monitoring: Proof of concept. *Build. Environ.* **2022**, *217*, 109064. [CrossRef]
79. Hong, J.; Kang, H.; Jung, S.; Sung, S.; Hong, T.; Park, H.S.; Lee, D.-E. An empirical analysis of environmental pollutants on building construction sites for determining the real-time monitoring indices. *Build. Environ.* **2020**, *170*, 106636. [CrossRef]
80. Tang, Z.W.; Ng, S.T.; Skitmore, M. Influence of procurement systems to the success of sustainable buildings. *J. Clean. Prod.* **2019**, *218*, 1007–1030. [CrossRef]
81. Zhang, C.; He, K.; Zhang, W.; Jin, T.; Ao, Y.; Rashid, R.S.M. Study on Mechanism of Factors Affecting Resilience of Prefabricated Building Supply Chain. *Adv. Civ. Eng.* **2023**, *2023*, 8870224. [CrossRef]

82. Lai, H.; Deng, X.; Chang, T.-Y.P. BIM-Based Platform for Collaborative Building Design and Project Management. *J. Comput. Civ. Eng.* **2019**, *33*, 05019001. [CrossRef]
83. Li, K.; Duan, T.; Li, Z.; Xiahou, X.; Zeng, N.; Li, Q. Development Path of Construction Industry Internet Platform: An AHP–TOPSIS Integrated Approach. *Buildings* **2022**, *12*, 441. [CrossRef]