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Evaluation of Safety Management of Smart Construction Sites from the Perspective of Resilience

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Abstract: In the context of green, low-carbon, and sustainable construction, the safety management of smart construction sites has been a key issue. Current related research mainly focuses on the application of technology, but lacks methods to evaluate the safety management level. Therefore, this research aims to construct a smart construction site safety management evaluation model from a resilience perspective. First, this research identified and screened the indicators initially based on the 4R resilience characteristics and 4M theory by analyzing the policy texts of smart construction site safety management. Then, through expert consultation, the ISM model of resilience indicators was established to determine the evaluation indicator system of smart construction site safety management. Next, the weight of each indicator was determined with the help of the analytic network process, and the evaluation criteria of the indicators were formulated according to the existing specifications and expert interviews; then, the evaluation model of smart construction site safety management was established. Finally, the feasibility of the model was proved through a case study. The findings of the research show that in terms of weights, management has the highest score, followed by media, man, and machine. However, more resilience measures are used for the safety management of machine than the other three in policy texts. Obviously, there is a deviation between weights and resilience characteristics. These findings help reveal the current situation of safety management at smart construction sites, which is of great significance for improving resilience. The findings also help smart construction sites to realize the upgrading of safety, efficiency, and greenness, and promote the sustainable development of smart construction sites as well as the construction industry.

Keywords: smart construction site; safety management; resilience; evaluation

Citation: Qian, Y.; Liu, H.; Mao, P.; Zheng, X. Evaluation of Safety Management of Smart Construction Sites from the Perspective of Resilience. *Buildings* **2023**, *13*, 2205. https://doi.org/10.3390/buildings13092205

Academic Editor: Irem Dikmen

Received: 3 August 2023
Revised: 26 August 2023
Accepted: 28 August 2023
Published: 30 August 2023

1. Introduction

Under the guidance of the sustainability goals, sustainable urban development is gradually being emphasized [1]. Infrastructure construction, as a necessary part of urban development, is changing from high energy consumption and high emissions to a new model of digitalization, intelligence, and greening. The smart construction site is one of the typical representatives of the transformation path of construction mode. At present, a variety of new technologies in the smart construction site have greatly improved the efficiency, management level, and serviceability of the construction site operation.

Generally speaking, construction sites have been plagued with long-standing safety problems, such as complex environments, difficulties in personnel management, frequent occurrence of safety accidents, difficulties in investigation and evidence collection, and difficulties in machinery safety management [2,3]. The construction industry continues to be one of the most dangerous industries [4]. Therefore, safety management is a theme that must be considered in the construction site management process. The smart construction site is a new type of construction means built on a high degree of informationization. Compared with the traditional construction site, the construction scale of the smart site is increasing, and the introduction of new technologies and the integration of multiple subsystems make the construction site more and more complex. It can be seen that although there are differences in technical applications and management means between smart construction sites and traditional construction sites, their safety management is still the top priority [5]. Nowadays, despite the existence of many smart construction site management platforms in the market, they face huge uncertainties in information interaction and have poor risk resistance [6]. When some of the functions of the management system are damaged due to emergencies, the system can easily be completely paralyzed if it lacks backup modules or fails to replenish them in time. This will result in a delay in the overall construction schedule and an unnecessary waste of manpower and resources. In addition, the smart construction site management system is more complicated than the traditional management system, making it difficult to ensure a reasonable deployment of emergency resources to maximize benefits. It is also hard to return to a certain functional level in a relatively short period of time after the occurrence of emergencies. Therefore, it is one-sided and costly to rely only on traditional safety management tools to protect against risks. Resilience theory not only takes into account the ability of the thing itself to resist risk, but also focuses on the whole change process in the whole system, so that the system can return to its prior state more quickly [7]. At the same time, resilience theory can learn from the experience of the impact of shocks or disturbances, improve the adaptive capacity to uncertain events [8], and optimize the system in the direction of greenness and efficiency. As a result, it is urgent to improve the recovery and adaptive capacity of safety management systems from a resilience perspective.

The scientific community has also conducted a wealth of research on smart construction site safety management, which mainly emphasizes the application of technology and system frameworks to achieve the goal of smart construction site safety management. However, it is not enough to improve safety management only by upgrading technical means. Existing studies have not yet systematized the indicators of smart construction site safety management. In addition, there is no proper model to evaluate the current state of smart construction site safety management. Resilience considers the recovery and adaptive capacity of a system, but construction project safety management systems have not yet emphasized resilience, and smart construction sites have paid even less attention to this concept. Although some results have been accumulated on resilience evaluation research of safety management, little attention has been paid to the safety management of smart construction sites.

To overcome these shortcomings, this research aims to develop a smart construction site safety management evaluation method based on the perspective of resilience. Specifically, it explores the following questions: (1) What is the evaluation system of smart construction site safety management, based on the perspective of resilience? (2) What are the evaluation indicator criteria for smart construction site safety management? (3) How can the evaluation of smart construction site safety management be realized? To achieve the above objectives, this research first analyzed the policy texts using Nvivo. Based on resilience characteristics and 4M theory, initial indicators of smart construction site safety management were identified and selected. Secondly, the ISM model was constructed based on expert consultation, and the interrelationships between the indicators of smart construction site safety management were sorted out. Final direct indicators were obtained and the evaluation indicator system was constructed. Then, after determining the weights of the indicators and evaluation criteria, the evaluation model of smart construction site safety management was constructed. Finally, the feasibility of the model was verified by taking a smart construction site as an example.

The main contributions of this research are in the following aspects: (1) Introduce a new perspective, the resilience perspective, to discuss smart construction site safety management. (2) Combine the 4R resilience characteristics and the 4M theory to code the policy text at three levels and construct a smart construction site safety management indicator system. (3) Develop an evaluation model of smart construction site safety management to assess the current situation of the safety management level. The findings of the research help improve the safety management level of the smart construction site, make it more resilient, and avoid falling into the dilemma of simple superposition of technical means. At the same time, through the scientific management measures of personnel and media, it helps to improve the safety management efficiency of the smart construction site, promote its green upgrading, and further promote the sustainable development of the smart construction site.

The rest of the research is structured as follows. Section 2 contains the literature review. Section 3 details the method used in this research. Section 4 describes the construction of the evaluation model for smart site safety management. Section 5 proves the feasibility of the constructed model with the help of a real case study. Sections 6 and 7 present the discussion and the conclusions, respectively.

2. Literature Review

2.1. Smart Construction Site Safety Management

Concepts such as smart cities and smart districts are emerging to achieve the sustainable development targets [9]. As one of the components of a smart city, a smart construction site integrates information technologies such as BIM, cloud computing, big data, the Internet of Things, and smart devices into various fields such as construction organization management and construction site management [10,11] to promote the upgrading of the traditional construction site and achieve fine site management. Construction safety has long been a thorny issue in the development of the construction industry. It is vital to ensure the safety of personnel and machinery at construction sites. Therefore, safety management is also a research hotspot of smart construction site management. With the development of smart construction sites, more and more smart technologies are being used at smart construction sites, providing a large number of system models and countermeasure suggestions for smart construction site safety management. For example, Rey proposed a digital system for construction site safety condition inspection using UAVs to provide timely information for site decision making [12]. Zhang established a framework for the construction site information management system based on blockchain and smart contracts to guarantee the safety supervision of projects [13]. Zhang proposed a method that combines computer vision and a real-time location system for proactive site safety management [14]. Thus, it can be seen that many achievements have accumulated in smart construction site safety management at this stage, but most of the research is limited to safety risk warning systems and the detection of site safety [5]. However, there is still a lack of methods and tools that can judge the application of technology in smart construction site safety management, namely the current state of smart construction site safety management. Therefore, it is urgent to develop an evaluation model of smart construction site safety management. The scientific community has noticed the necessity to conduct research in this area; for example, Liu identified indicators for the evaluation of smart construction site safety management based on BIM technology [15]. However, the occurrence of safety accidents is not only related to technology and equipment, but also closely linked to humans, the environment, and management. This is also proved by the 4M theory of risk source. In the 4M theory, four main factors, Man, Machine, Media, and Management, are considered together [16,17]. Most traditional construction site safety management research is also based on the 4M theory [18]. These four factors work together throughout the process of the smart construction site being disturbed. Therefore, the 4M theory helps guide the safety management evaluation of the smart construction site.

2.2. Feasibility of Safety Management Research Based on Perspective of Resilience

Traditional safety management aims to reduce the number of accidents [19], while safety management that only focuses on resisting the occurrence of risks is one-sided and costly. In complex and uncertain work environments, it is important to take a fresh perspective on safety and anticipating risks [20] and take proactive measures to deal with unexpected events. Resilience is a new perspective that can achieve these goals. The concept of resilience is derived from the adaptive cycle model proposed by Holling and Gunderson and applied to various fields such as mechanics, psychology, and social sciences [21]. Resilience considers how to improve the "recovery" and "adaptation" capabilities of a system in unexpected situations, reduce recovery costs and time, and prepare for future emergencies [22]. At present, most of the research on resilience is focused on the field of public management [23]. With the depth of research, resilience has gradually been introduced into the safety management of construction projects in recent years [24,25]. For example, Rodrigues combined the concept of resilience engineering and unmanned aircraft systems technology for safety planning and control on construction sites to facilitate safety management [26]. In the field of resilience evaluation, some scholars have also conducted research, mainly focusing on the elements [27], properties [28], and influencing factors of resilience [29]. Of course, there are some research results in the evaluation of the resilience of safety management. For example, Zhu proposed a theoretical framework and key safety management factors for a construction safety management system based on resilience theory [30]. Wang established a safety management evaluation indicator system comprising 25 indicators for high-speed railroad construction projects in mining areas based on the concept of resilience and constructed a resilience evaluation model [31]. Zhang identified indicators through the literature and expert opinions and established a sewer network resilience evaluation framework [32]. In general, the most mainstream evaluation principle in resilience theory at this stage is the 4R principle proposed by Bruneau in 2003, which contains the four main characteristics of robustness, resourcefulness, redundancy, and rapidity [33]. Robustness refers to the system's ability to reduce the potential for accidents before a shock and to mitigate the negative consequences caused by an emergency when a shock occurs. Resourcefulness means that the system has a certain reserve of emergency resources and can use them rationally to maximize the benefits. Redundancy means that a system has a certain amount of replaceable spare modules, so that when the functions of some equipment in the system are seriously affected by the shock, the spare parts can participate promptly to make the whole system operate normally. Rapidity represents the ability to recover quickly after a shock [33]. However, the application of resilience in the construction safety management system has not yet received enough attention [34], and there is even less involvement in smart construction site safety management. Therefore, it is of great importance to explore the evaluation model that affects the smart construction site safety management in the resilience background.

2.3. Research Gap

With the emergence of smart construction sites, scholars have researched smart construction site safety management. But most of them only emphasize the application of information technology and lack specific methods to judge the current situation of smart construction site safety management. Considering the shortcomings of traditional safety management, resilience can not only reduce the occurrence of risks, but also improve the recovery ability of safety management systems. Although resilience is gradually used for the safety management of construction projects, it is rarely involved in smart construction site safety management. As a result, an evaluation model for smart construction site safety management based on a resilience perspective is required.

3. Methods

The research framework of this research is shown in Figure 1.

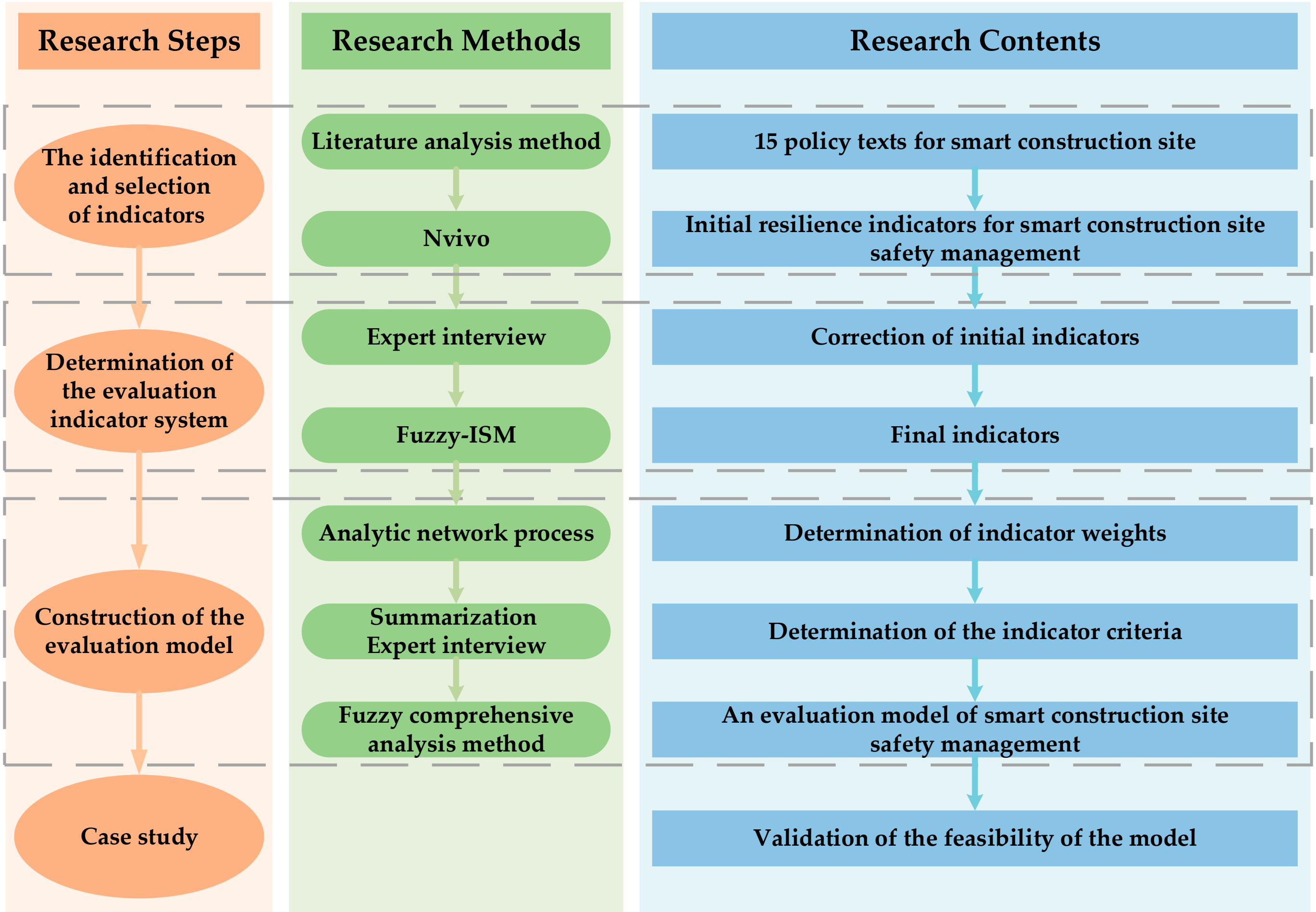

Figure 1. Research framework.

The first step is the identification and selection of indicators. First, 15 policy texts related to smart construction sites were found based on the literature analysis method. Second, this research applied Nvivo 12 Plus to obtain initial resilience indicators for smart construction site safety management. In this step, a randomly selected portion of 15 policy texts were imported into Nvivo. Based on the resilience theory, keywords and phrases in the texts involving 4R resilience characteristics were then extracted and conceptually named to form an open coding. Subsequently, main categories were created by integrating and deleting previously subsidiary conceptual categories to complete the axial coding. At last, according to the 4M theory, core categories consisting of 4M factors were determined by systematic analysis. During this step, the selective coding was completed [35]. In order to ensure the accuracy and reliability of the results, finally, a saturation test was required. Specifically, the remaining policy texts were required to be coded at three levels. If no new category appears after coding, the data are considered saturated [36]. After the saturation test, the indicator framework was derived, and the initial resilience indicators for smart construction site safety management were obtained.

The second step is the determination of the evaluation indicator system. To ensure the validity and accuracy of the indicators, 18 experts were invited to revise the initial indicators. Fuzzy-ISM utilizes fuzzy numbers instead of 0 and 1 to describe fuzzy relationships between indicators and it can transform complex content into a hierarchical system and demonstrate the hierarchical relationship between indicators clearly [37]. Therefore, Fuzzy-ISM was used to determine the final smart construction site safety management indicator system. In addition, the hierarchical relationship between the indicators can be obtained when conducting Fuzzy-ISM. It is the necessary information for the subsequent step of constructing the network structure in the ANP method.

The next step is the construction of the evaluation model. First, it is necessary to determine the weight of each indicator. The analytic network process (ANP) can measure the interrelationship of indicators in the system objectively and obtain the weights and total ranking of indicators [38]. Thus, it was used to determine the weights of the indicators in this research. Next, the evaluation criteria needed to be established. Since there are no evaluation criteria for smart construction site safety management, the criteria for these evaluation indicators were determined by summarizing the standard texts and discussing them with experts. Finally, with the help of the fuzzy comprehensive analysis method, the evaluation model of smart construction site safety management was constructed based on the determination of weights and evaluation indicators. The fuzzy comprehensive analysis method was used because it not only considers the hierarchy of evaluation objects but also gives full play to human experience, which can make the evaluation results more reliable [39,40].

Finally, we used a case study. Constructing an evaluation model requires verifying its feasibility and validity. Evaluations conducted only at the theoretical level are ultimately weak [41]. Therefore, Project A was selected for the evaluation of smart construction site safety management in this research.

4. Model Development

4.1. Identification and Selection of Indicators

The policy texts under implementation will better reflect the reality of smart construction site safety management and resilience than the past literature, and the construction standards of smart construction sites have not yet been unified. In addition, this research focused on the safety management of smart construction sites in China. Therefore, this research was based on the keywords (1) safety management (“safety guidelines”, “regulatory approaches”, “technical standards”, etc.), (2) “smart construction site”, “construction informationization”, “smart construction”, etc. Fifteen relevant policy texts were finally selected from the official websites of housing and construction departments of Chinese provinces and cities.

On the one hand, resilience theory can deepen the understanding of the components of the smart construction site safety management system. Enhancing the resilience of the system can avoid the occurrence of accidents while reducing the damage caused by shocks [42], and effectively improve the safety of the smart construction site. On the other hand, the source of accidents is largely attributed to the hazard source [43]. As a result, the evaluation of smart construction site safety management can be based on risk source theory, which considers the resilience of the system from man, machine, media, and management perspectives. However, in the actual response to the entire risk process, the indicators of these four perspectives often work together. Therefore, it is necessary to establish a two-dimensional matrix between the 4R resilience characteristics and the 4M theory, and to obtain the smart construction site safety management evaluation indicators from the two dimensions together.

4.1.1. Based on the 4R Resilience Characteristics

In this research, the judgment criterion for selecting smart construction site safety management indicators based on the 4R resilience characteristics was to ensure that the selected indicators must satisfy one of the characteristics of resilience. Taking “Person identification” as an example, in the smart construction site safety management system, the function can ensure personnel safety supervision by identifying whether construction personnel wear protective equipment such as safety helmets and vests. It can also assist in the efficient conduct of professional supervision through the automatic identification of the personnel number and the project progress. It emphasizes the safety of construction personnel, thus reducing construction accidents. Therefore, “Personnel identification” can be considered to be consistent with robustness. In indicator selection, Nvivo was used to perform open coding on 12 policy texts that were randomly chosen from a pool of 15, and the remaining 3 policy texts were used as data for the saturation test. After coding, 29 initial indicators were obtained. To generalize the indicators, axial coding was performed based on open coding, and 13 main categories and their corresponding subcategories were obtained. The classification nodes of each indicator's 4R resilience characteristics and the categories are shown in Table 1.

Table 1. Resilience indicators of smart construction site safety management system.

Main Category	Subcategories	R1	R2	R3	R4
Auxiliary personnel management	Personnel hierarchical authorization	√	√		
	Person identification	√			
	Personnel information management		√		
Analytical support for decision making	Assistance to personnel in decision making		√		√
	Visual aid analysis		√		
Promotion of personnel communication and collaboration	Communication skills		√		√
	Collaboration skills		√		√
Equipment failure resilience	Partial function substitutability of equipment	√		√	
	Equipment and system vandalism prevention	√		√	
	Equipment with fast response capability		√		√
Backup and expansion capability	Backup capability	√		√	√
	Expansion of functions and potential	√	√		
Early warning and emergency capability	Emergency response capability				√
	Early warning capability	√			√
Data analysis and processing capability	Adoption of cloud architecture		√		
	Positioning function		√		√
	Data acquisition and transmission		√		
	Data processing and management		√		
	Data hierarchical storage and processing		√		
Education of employees	Employee safety education	√	√		
	Employee skills training	√	√		
Ability to integrate functions	Integration of environmental monitoring	√			
Real-time environmental data	Real-time acquisition		√		√
	Real-time processing		√		√
Harsh environment resistance	Large operating temperature range	√	√		
	Inconsistent ability of equipment to resist harsh environments	√	√		
Accuracy of environmental monitoring	High environmental monitoring accuracy and fast response				√
Richness of monitoring points	Monitoring with redundancy			√	
	Multiple environmental monitoring points			√	
Total (number of nodes)		204	204	94	179

Note: R1 represents "Robustness"; R2 represents "Resourcefulness"; R3 stands for "Redundancy"; R4 stands for "Rapidity".

4.1.2. Based on the 4M Theory

As mentioned in the previous section, the indicators classified by their resilience characteristics were obtained. The final step in text coding analysis is selective coding. Therefore, based on the 4M theory, the codes were summarized and organized with the help of Nvivo. Finally, four selective codes were obtained, namely man, machine, media, and management, as shown in Figure 2. The three policy texts left behind were tested for theoretical saturation, and no new category appeared in the results. Therefore, the constructed indicators are saturated and can be analyzed next [36].

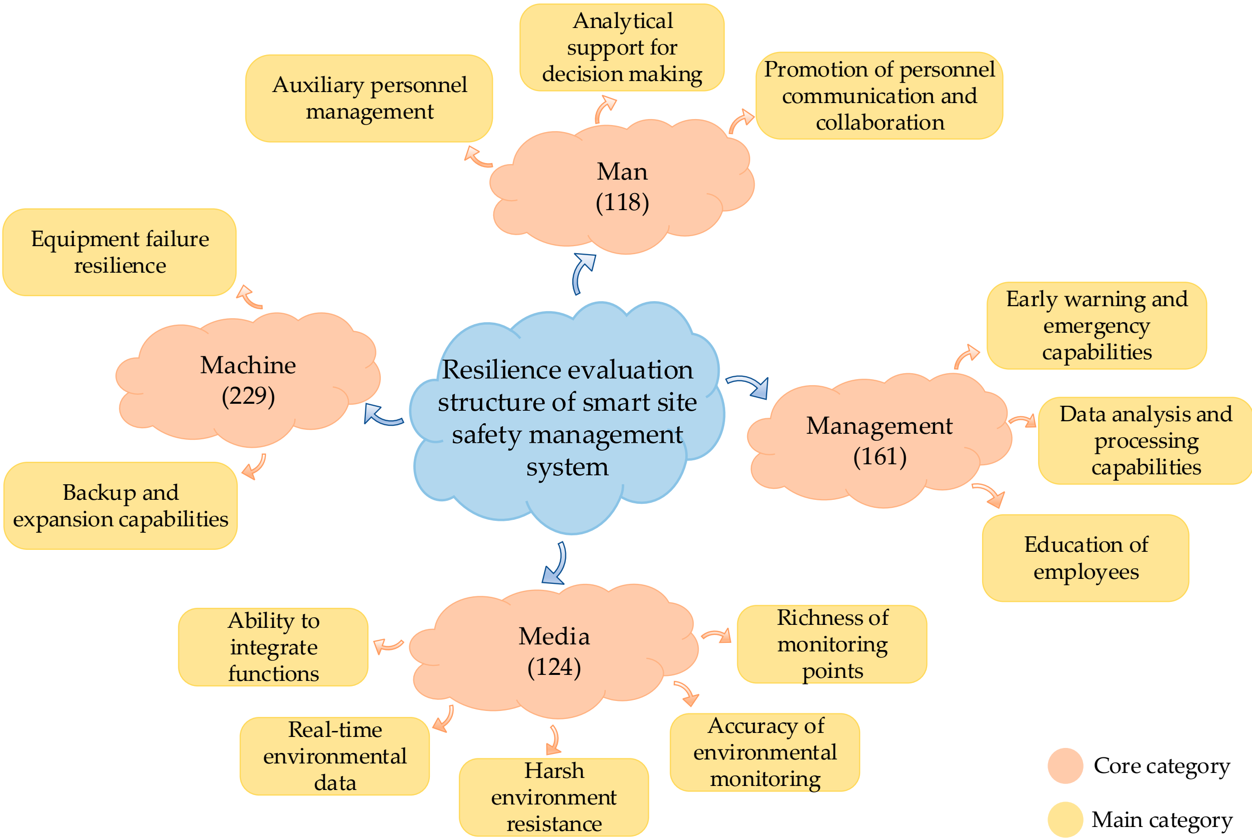

Figure 2. Resilience indicators by 4M classification.

After completing the classification of the indicators of smart construction site safety management, through quadratic matrix coding, the reflection of the 4R resilience characteristic under each 4M factor was further examined, as shown in Table 2.

Table 2. The reference point of the resilience characteristic under each 4M factor.

	Robustness	Resourcefulness	Redundancy	Rapidity
Man	12.31%	57.64%	0.35%	29.70%
Machine	32.93%	17.13%	30.08%	16.22%
Media	32.67%	10.17%	19.60%	37.57%
Management	29.24%	41.28%	0%	29.48%

As can be seen from the above table, the current policy texts pay more attention to the resourcefulness of man and management, which means the optimization of relevant decisions and the reasonable deployment of resources under limited resource reserves. At the same time, there are requirements for the robustness of machine and the rapidity of media, meaning the ability to absorb and resist shocks and the ability to respond and recover quickly. Combined with the ratio and the code number, the robustness of machine and the resourcefulness of man are more considered. As a smart construction site safety management system mainly serves to ensure the safety of people and machines, it is very important for a construction site to make machines more robust and people more resourceful. On the one hand, it enables people to make better decisions and improves the overall resource allocation of the system. On the other hand, it improves the resistance of machines to better cope with shocks and minimize the damage caused by risks.

4.2. Construction of the Evaluation Indicator System

As discussed in the preceding section, the Fuzzy-ISM model uses fuzzy numbers instead of 0-1 relationships to form a matrix that can effectively describe the possible fuzzy relationships among the indicators [44]. Therefore, the method was chosen in this research to explore the indicators of smart construction site safety management and the hierarchical relationship between the indicators to ensure that the final evaluation indicators can accurately reflect the resilience of smart construction site safety management. The methodological steps of the Fuzzy-ISM are specified in Figure 3.

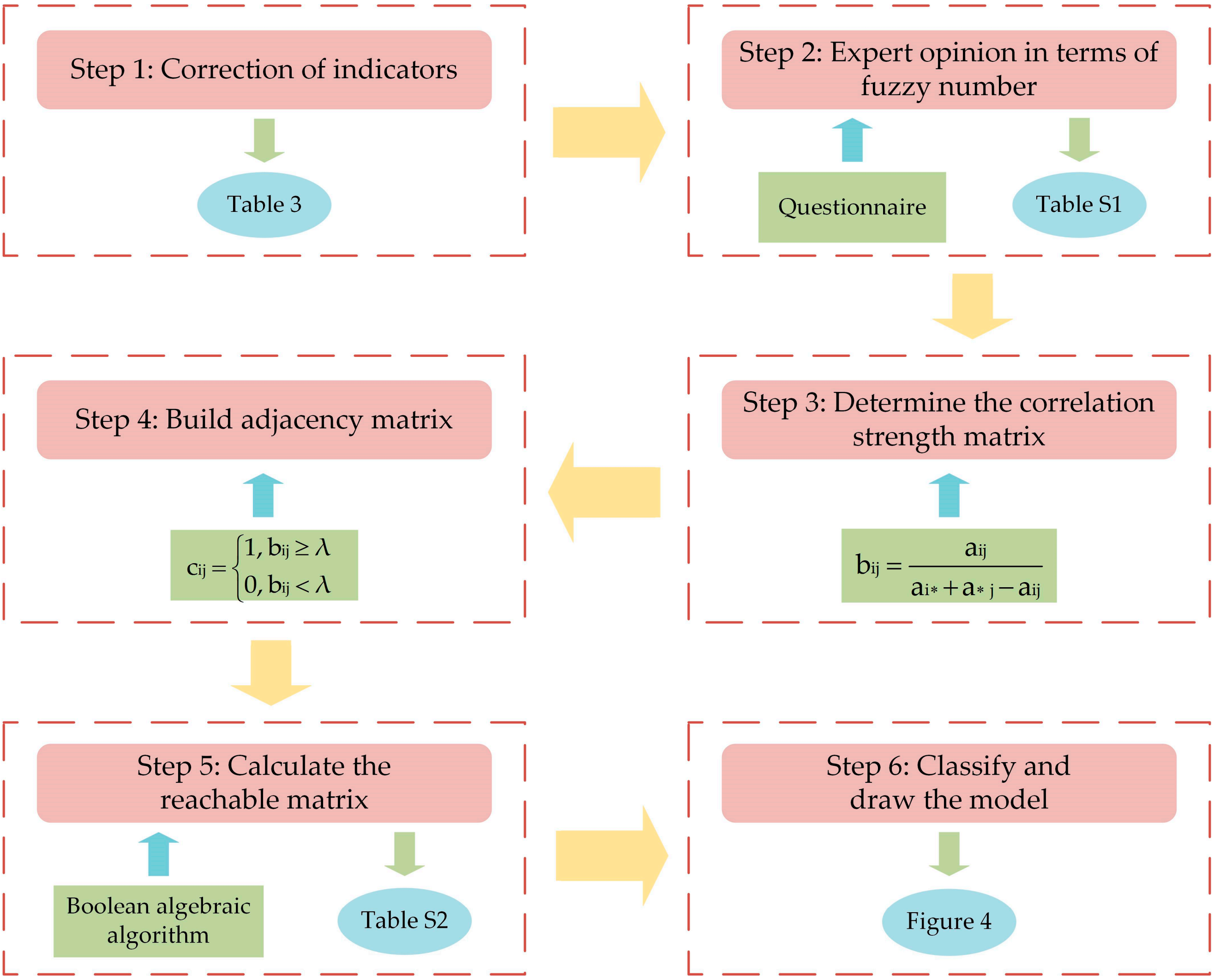

Figure 3. The process of Fuzzy-ISM. Note: (1) In the formula for step 3, a_{ij} is the value of row i and column j in the fuzzy correlation matrix, which is shown in Table S1; a_{i*} is the summation of the elements of row i of the matrix; a_{*j} is the summation of the elements of column j of the matrix. In step 4, a threshold λ is set to remove less influential relationships. Through expert consultation and experiments, λ = 0.052 was finally chosen in this research. (2) The final revised indicators are shown in Table 3. Table S2, detailed in the Supplementary Material, revealed the relationship between indicators.

Table 3. The revised indicators.

Category	Code	Indicators
Man	S1	Analytical support for decision making
	S2	Personnel management
	S3	Person identification
	S4	Promotion of personnel communication and collaboration
Machine	S5	Backup and replacement capability
	S6	Expansion of functions and potential
	S7	Equipment and system vandalism prevention
	S8	Equipment with fast response capability
Media	S9	Ability to integrate function
	S10	Richness of monitoring points
	S11	Accuracy of environmental monitoring
	S12	Harsh environment resistance
	S13	Real-time environmental data
Management	S14	Education of employees
	S15	Early warning and emergency capability
	S16	Adoption of cloud architecture
	S17	Positioning function
	S18	Data management

The process of indicator correction, questionnaire completion, and threshold λ determination in the above steps involved experts. Some research suggests that 10–18 experts are appropriate for a Delphi group [45]. Thus, 18 experts were invited to participate in this segment who are engaged in related work on smart construction sites. Among them, 15 experts have been working for more than 5 years. In terms of the nature of their work, there are six professors from universities, six corporate personnel who undertake the business of smart construction sites, and six government personnel.

It is not a good idea to use too many indicators in the evaluation process [46]. Therefore, experts were invited to make further corrections to the above indicators. After expert discussion, "Personnel hierarchical authorization" and "Personnel information management" in the subcategories were merged into "Personnel management". "Backup capability" and "Partial function substitutability of equipment" were merged into "Backup and replacement capability". "Data processing and management", "Data hierarchical storage and processing", and "Data acquisition and transmission" were combined into "Data management". The final revised indicators are shown in Table 3. The fuzzy correlation matrix of indicators and the reachable matrix calculated are shown in Tables S1 and S2 in the Supplementary Material. According to concepts such as reachable set and prior set, the indicators of smart construction site safety management were hierarchically divided. The final interpretative structural model of the indicators of smart construction site safety management is shown in Figure 4.

Due to the long influence path of the root layer indicators, the impact on smart construction site safety management is slow. Therefore, the apparent layer and middle layer indicators were determined as the final evaluation indicators. The graph of the final constructed evaluation indicator system of smart construction site safety management is shown in Figure 5. The number below the indicator in Figure 5 represents the code number corresponding to the indicator under different resilience characteristics.

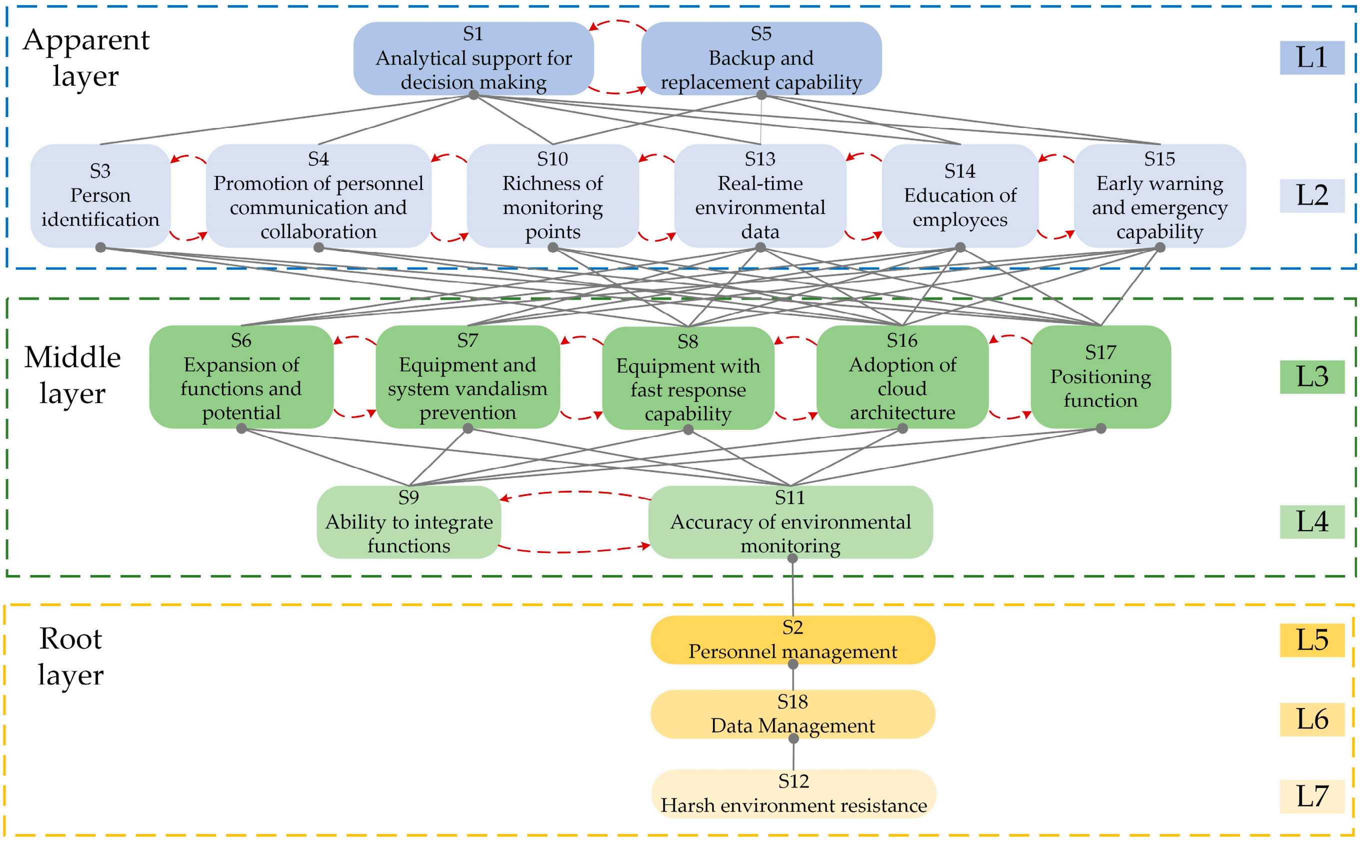

Figure 4. Interpretation structure model of indicators of smart construction site safety management.

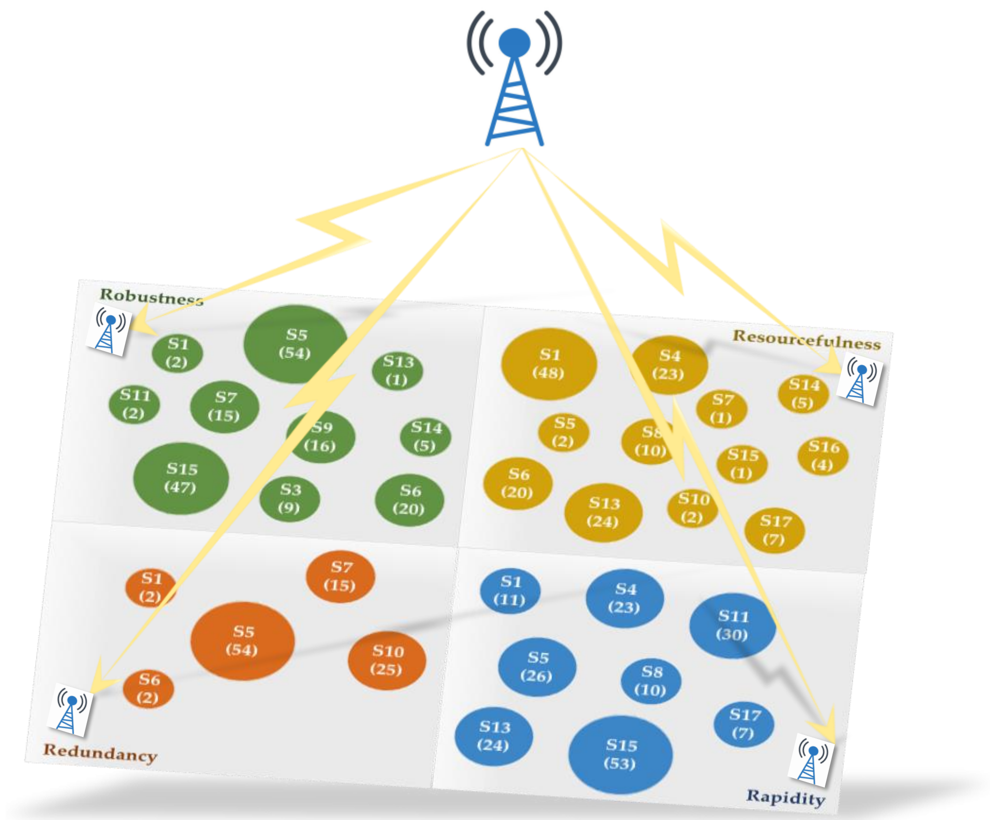

Figure 5. Evaluation indicator system.

4.3. Construction of the Evaluation Model

4.3.1. Determination of Weights

After constructing the smart construction site safety management indicator system, the next step is the calculation of weights. An analytic network process was selected to determine the weight of each indicator. The basic steps are as follows.

Step 1: The expert interviews were used to determine whether the indicators were internally independent, and the dependency and feedback relationship of each indicator.

Step 2: The correlations among the indicators were input into Super Decision to construct the network structure.

Step 3: The comparison matrices of secondary indicators (man, etc.) and tertiary indicators (S15, etc.) were constructed to form the secondary and tertiary indicator importance questionnaire.

Step 4: The experts were invited to complete the questionnaire, and the importance degree was assigned using the 1–9 scale method.

Step 5: The questionnaire results were analyzed using Super Decision software, and the hypermatrix was constructed to calculate the weights.

The experts in the steps were the same as those selected for the construction of the indicator system. Eighteen experts discussed the interpretative structure model diagram obtained previously and the fuzzy correlation matrix between the indicators, and finally complemented the correlations between S1 and S13; S4 and S13, S14; and S5 and S1, S13. After the experts completed the questionnaire, the ratings were summarized and averaged to obtain the final comparison matrices. To ensure the validity of the questionnaire results, a consistency test was required. According to previous research, the comparison matrix is consistent only if the value of the consistency ratio (CR) is less than 0.1 [47]. Therefore, the CR was calculated for all comparison matrices and the results show that values of CR were all less than 0.1, indicating that the consistency test was passed. Finally, the weights of the indicators were obtained by processing the data through the software and are shown in Table 4.

Table 4. Weight of each indicator.

Category	Weight	Indicator	Weight
Man	0.247672	S1 Analytical support for decision making	0.005057
		S3 Person identification	0.210437
		S4 Promotion of personnel communication and collaboration	0.032178
Machine	0.128442	S5 Backup and replacement capability	0.009634
		S6 Expansion of functions and potential	0.024269
		S7 Equipment and system vandalism prevention	0.019844
		S8 Equipment with fast response capability	0.074695
Media	0.295949	S9 Ability to integrate functions	0.109917
		S10 Richness of monitoring points	0.028938
		S11 Accuracy of environmental monitoring	0.112172
		S13 Real-time environmental data	0.044922
Management	0.327938	S14 Education of employees	0.051581
		S15 Early warning and emergency capability	0.052841
		S16 Adoption of cloud architecture	0.133831
		S17 Positioning function	0.089685

4.3.2. Determination of the Evaluation Criteria

Since there is less research on the evaluation of smart construction site safety management at this stage, the corresponding evaluation criteria have not yet been formed. Therefore, according to the Technical Standard for Information Systems of Construction Site Supervision And Management (JGJ/T 434-2018) [48], the Technical Standard for Intelligent Safety Supervision of Building Construction (DB32/T 4175-2021) [49], the Technical

Standard of Implementing Smart Construction Sites (DB13(J)/T 8312-2019) [50], Technical Standard for Smart Construction Sites (DB64/T 1684-2020) [51], and the Technical Specification for Smart Construction Sites (DB11/T 1710-2019) [52], combined with relevant case investigations, the preliminary evaluation criteria for safety management of smart construction sites were summarized. To enable the feasibility of the constructed evaluation criteria, the 18 experts were invited once again to judge and comment on the criteria. The evaluation criteria were then revised according to experts' comments and the revised criteria were fed back to the experts again. The experts had no disagreement with the revised evaluation criteria this time. Finally, the evaluation criteria of smart construction site safety management were obtained, shown in Table 5.

Table 5. The final evaluation criteria.

Category	Indicator	Evaluation Criteria
Man	S1 Analytical support for decision making	The number of areas covered with the ability to perform statistical analysis of information data
	S3 Person identification	The number of smart and biometric modules offered, and the number of scenes in which they are used
	S4 Promotion of personnel communication and collaboration	The number of participants involved in the multi-collaborative management of engineering construction
Machine	S5 Backup and replacement capability	The number of modules with automatic data backup, video history replay, and video download functions
	S6 Expansion of functions and potential	Whether it is possible to realize the expansion of system functions by adding business modules according to actual needs
	S7 Equipment and system vandalism prevention	Whether the designed software has encryption, whether the hardware has waterproof and drop-proof functions
	S8 Equipment with fast response capability	Responsiveness of the platform and critical equipment in terms of page response, backup/restore time of logs
Media	S9 Ability to integrate functions	The number of interface support tools for various types of IoT monitoring equipment at construction sites
	S10 Richness of monitoring points	The number of types that reflect the amount of redundancy in product design
	S11 Accuracy of environmental monitoring	Technical parameters related to the efficiency of key equipment used on sites (cameras, various sensors)
	S13 Real-time environmental data	The number of devices that can automatically monitor, display in real time, and synchronize the transmission of environmental data on sites
Management	S14 Education of employees	Whether to provide employee education-related online training, course exam management, and richness of content
	S15 Early warning and emergency capability	The number of types of warnings provided by the sites
	S16 Adoption of cloud architecture	The number of types of users involved in the platform
	S17 Positioning function	The number of types of positioning technology

Among them, S1, S3, S4, S5, S9, S10, S13, S15, S16, and S17 were quantitative indicators, and S6, S7, S8, S11, and S14 were qualitative indicators. To avoid the influence of indicator attributes on the evaluation, all indicators needed to be normalized. For quantitative indicators, taking S16 "Adoption of cloud architecture" as an example, the measure of this indicator is the number of types of users involved in the platform. According to the relevant standard texts, it is found that the user layer is generally divided into six categories, i.e., competent departments, construction units, design and survey units, construction companies, supervisory units, and practitioners. When S16 = n ($n \leq i$, $i = 6$), the evaluation value of the indicator is equal to n/i. When S16 > i, the evaluation value is equal to 1. The evaluation values for the remaining indicators were obtained in the same way. The value of each quantitative indicator i was verified as appropriate by the experts, and the results are shown in Table 6. For qualitative indicators, the evaluation set was determined first, and [0, 1] was divided into five subintervals corresponding to the evaluation set, and the average value was taken as the evaluation value of the indicator after scoring by experts. The criteria for determining the evaluation value of qualitative indicators are shown in Table 7.

Table 6. Each quantitative indicator's i-value.

Indicator	i-Value	Indicator	i-Value
S1	9	S3	3
S4	7	S5	8
S9	10	S10	12
S13	9	S15	7
S16	6	S17	7

Table 7. Criteria for the evaluation value of qualitative indicators.

Indicator	Evaluation Value				
	0.8–1	**0.6–0.8**	**0.4–0.6**	**0.2–0.4**	**0–0.2**
S6	high	relatively high	average	relatively low	low
S7	high	relatively high	average	relatively low	low
S8	high	relatively high	average	relatively low	low
S11	high	relatively high	average	relatively low	low
S14	high	relatively high	average	relatively low	low

4.3.3. Model Construction

In order to obtain the evaluation level of smart construction site safety management, the fuzzy comprehensive evaluation method was used to construct the model based on the determination of the indicator weight. The key steps of the method are as follows.

Step 1: The set of evaluation indicators was determined.

Step 2: Five evaluation levels were determined according to the qualitative indicator evaluation value table [53]. The following evaluation set V can thus be established: {V1, V2, V3, V4, V5} = {excellent, good, average, poor, very poor}. The range of affiliation values for each level is shown in Table 8.

Table 8. The range of affiliation values for each level.

Affiliation Value	[0.8, 1]	[0.6, 0.8)	[0.4, 0.6)	[0.2, 0.4)	[0, 0.2)
Evaluation Level	excellent	good	average	poor	very poor

Step 3: Each evaluation indicator was quantified to obtain the evaluation value, and the fuzzy relationship matrix was obtained.

Step 4: The weight vector was determined according to the following formula:

$$W = (\omega_1, \omega_2, \ldots, \omega_n). \tag{1}$$

where W represents the weight vector and ω indicates the weight of each indicator.

Step 5: Based on the weight vector and the fuzzy relationship matrix, the evaluation result vector was calculated from the equation below:

$$B = W \cdot R. \tag{2}$$

In this equation, B is the evaluation result vector and R represents the fuzzy relationship matrix. The evaluation level was obtained according to the principle of maximum affiliation.

5. Case Study

To verify the feasibility of this evaluation model, a typical smart construction site was selected as the evaluation object in this section, which had the value of analysis and evaluation because the smart business of the site was entrusted to an excellent enterprise with a certain scale, mature management, and certain praise in the industry.

5.1. Case Overview

Project A is located in Chengdu, Sichuan, China, and its main function is as an office building and commercial package. The project consists of a seventh-floor office building and a second-floor commercial building with a total construction area of 165,600 m^2. The building heights of the project are 31.85 m and 11.75 m, respectively. Construction of the project started in March 2019 and ended in May 2022. The smart business of the project is undertaken by a national high-tech enterprise. Specifically, from the four aspects of man, machine, media, and management, the status of each aspect of Project A is as follows.

5.1.1. Man

This smart construction site system uses the real-name access control system to collect and manage information such as workers' access to the site. It ensures multi-unit collaboration through platform docking and linkage technology, and supports seven types of file sharing such as project electronic drawings. It provides seven types of summarization functions such as data mining by statistical analysis data warehouse to assist personnel in analyzing and making decisions.

5.1.2. Machine

The system has good stability and reliability, and functions such as effective transfer or rapid recovery can be guaranteed in case of faults. The system retains interfaces for connection with other automation systems while taking into account future scientific developments and the application of new technologies as much as possible. A variety of auxiliary functions are added to the equipment to prevent it from being easily damaged. There are five types of modules with automatic data backup functions.

5.1.3. Media

The access sensor equipment adopts fingerprint collection, and the smart construction site system realizes checking the body temperature condition of personnel within 3 s. The system provides six types of interfaces such as environmental monitoring interfaces. It provides five types of parameter collection functions such as particulate matter concentration. Furthermore, it retains some leeway in the control capacity of the project equipment, involving ten categories of available backup equipment.

5.1.4. Management

The smart construction site system is mainly for four main subjects: competent departments, construction units, construction companies, and practitioners. It realizes two types of positioning functions for personnel and materials. Basically, it provides three types of warnings in terms of progress, environmental monitoring, and defense zone shots. It uses the Internet and multimedia display to develop the traditional party-building work into an intelligent and integrated management mode.

5.2. Evaluation Process

The actual value of the quantitative indicator was determined through on-site investigation, combined with the solution announced by the enterprise. The quantitative indicator was calculated based on the formula n/i. For the qualitative indicator, the original 18 experts were invited to score, and the average value was finally taken as the qualitative indicator evaluation value. The detailed results are shown in Table 9.

Table 9. Summary of the evaluation indicator data for the smart construction site case study.

Category	Indicator	Actual Value	Evaluation Value
Man	S1	7	0.7778
	S3	2	0.6667
	S4	7	1.0000
Machine	S5	5	0.6250
	S6	/	0.3150
	S7	/	0.4900
	S8	/	0.7250
Media	S9	6	0.6000
	S10	10	0.8333
	S11	/	0.5050
	S13	5	0.5556
Management	S14	/	0.7050
	S15	3	0.4286
	S16	4	0.6667
	S17	2	0.2857

Note: "/" shows that the indicator has no actual value.

The fuzzy relationship matrix of man, machine, media, and management was constructed using the evaluation values as follows:

$$R_{Man} = \begin{bmatrix} 0.7778 \\ 0.6667 \\ 1.0000 \end{bmatrix},\ R_{Machine} = \begin{bmatrix} 0.6250 \\ 0.3150 \\ 0.4900 \\ 0.7250 \end{bmatrix},\ R_{Media} = \begin{bmatrix} 0.6000 \\ 0.8333 \\ 0.5050 \\ 0.5556 \end{bmatrix},\ R_{Management} = \begin{bmatrix} 0.7050 \\ 0.4286 \\ 0.6667 \\ 0.2857 \end{bmatrix}$$

The weight vectors of each secondary indicator were the following:

$$W_{Man} = (0.02042, 0.84966, 0.12992)$$

$$W_{Machine} = (0.075, 0.18895, 0.1545, 0.58155)$$

$$W_{Media} = (0.37141, 0.09778, 0.37902, 0.15179)$$

$$W_{Management} = (0.15729, 0.16113, 0.4081, 0.27348)$$

The results of the fuzzy single-indicator evaluation can be obtained:

$$B_{Man} = 0.7123,\ B_{Machine} = 0.6037,\ B_{Media} = 0.5801,\ B_{Management} = 0.5302$$

The results of the fuzzy single-indicator evaluation were used to construct a fuzzy relationship matrix for the second-level fuzzy comprehensive evaluation:

$$R = \begin{bmatrix} 0.7123 \\ 0.6037 \\ 0.5801 \\ 0.5302 \end{bmatrix}$$

The weight vector of the primary indicator was

$$W = (0.247672, 0.128441, 0.295949, 0.327938)$$

Finally, the second-level fuzzy comprehensive evaluation result was obtained ($B = 0.5995$). Therefore, the smart construction site safety management level is "average".

6. Discussion

Overall, in terms of weights, "Management" (0.3279) > "Media" (0.2959) > "Man" (0.2477) > "Machine" (0.1284). However, in terms of the number of resilience codes, "Machine" has 229, the highest number, and the code number of indicators with higher weights is all relatively small. From the perspective of the model application, for Project A, its safety evaluation scores are higher for "Man" and "Machine", and lower for "Media" and "Management". This indicates that there is a certain deviation between the current policy texts related to smart construction site safety and the present safety management measures and the actual importance degree of indicators. Resilience characteristics in current policy texts are not sufficiently considered, focusing mainly on "Machine", especially in terms of robustness and redundancy. These resilience characteristics mainly act on the initial stage of risk to resist the occurrence of risk [54], which further verifies that the current smart construction site is influenced by traditional safety management thinking and lacks a resilience perspective to deal with the new situation in an informationization context. Therefore, in the subsequent policy release, attention should be paid to the further refinement of "Man", "Media", and "Management", thus balancing the content of the relevant standards in distribution.

6.1. Man

In the evaluation model constructed, the indicator of "Man" accounts for 0.2477 of the weight, which is usually considered the most important indicator in traditional safety management. However, the platform, hardware, and software of the smart construction site can alleviate problems such as human error and low cultural level to some extent, so it is not prominent in the weight analysis. Specifically, the weight of "Person identification" is the largest (0.2104), followed by "Promotion of personnel communication and collaboration" (0.0322), and lastly, "Analytical support for decision-making" (0.0051). "Person identification" is the basis of personnel safety under the smart construction site. For example, face recognition systems, equipment for real-time monitoring of site personnel movements, Bluetooth personnel positioning, and functions of platform alarms, capture maps, and voice prompts are based on person identification [55,56]. Realizing the improvement in person identification ability can effectively strengthen the dynamic management of construction workers and reduce the accident rate, which plays a vital role in guaranteeing safety. However, the number of resilience codes and the corresponding evaluation value in the case of this indicator are the lowest, indicating that inadequate resilience measures of person identification are reflected in relevant policy texts on the current safety management of smart construction sites, and the problem of insufficient safety assurance ability may arise. The weights of "Promotion of personnel communication and collaboration" and "Analytical support for decision-making" are not high, but the number of codes corresponding to both of them is large, which shows that the two indicators are currently given more importance in smart construction sites.

Combined with the actual case, the evaluation value of "Promotion of personnel communication and collaboration" earns a perfect score. Investigation shows that the site shares alarm systems and video resources with supervisory units through platform docking and linkage technology to ensure that multiple units work in collaboration with each other. It provides an enterprise-level smart construction site platform to meet the control of smart construction sites in each project department. It supports the uploading of enterprise or project standard data specifications, electronic drawings, and so on, with a total of seven types of file sharing. The above measures are worth learning for other smart construction site managers. The ratings of "Person identification" and "Analytical support for decision-making" are both good, with values of 0.6667 and 0.7778, respectively. It shows that this smart construction site performs well in terms of "Man", but there is still room for improvement. In terms of "Person identification", the biometric module of various ways should be added and applied. To "Analytical support for decision-making", the operator should be assisted in visualizing the operation. Also, by providing more devices and platforms with instant communication capabilities, the statistical analysis results can be better reported and shared.

6.2. Machine

"Machine" has the lowest weight of 0.1284, but this does not directly indicate that it is not important. The reason for this is that the robustness, redundancy, and other durable and replaceable aspects can be achieved to some extent by improving the quality of the equipment at the site and increasing the number of spares and replacements available. "Machine" includes "Equipment with fast response capability", "Expansion of functions and potential", "Equipment and system vandalism prevention", and "Backup and replacement capability", with weights of 0.0747, 0.0243, 0.0198, and 0.0096, respectively. The weight of "Equipment with fast response capability" is the largest, but its code number ranks last in "Machine", which indicates that the current smart construction site policy texts need to increase requirements for equipment quality. When the equipment has a shorter response and backup recovery time, the quality of smart construction sites can be increased. The other three indicators have relatively balanced weight scores and relatively high code numbers, which confirm that nowadays, smart construction sites pay enough attention to "Expansion of functions and potential", "Equipment and system vandalism prevention", and "Backup and replacement capability".

From the model application, the indicator "Equipment with fast response capability" has a value of 0.7250, which is a good rank and consistent with its higher weight. The indicator "Backup and replacement capability" with the highest number of resilience codes has a good value rating (0.6250), but it has the lowest weight, ranking only 14th in the weights of all indicators. The indicator "Expansion of functions and potential", which is in the middle of the list, has a poor value rating (0.3150). The value of the indicator "Equipment and system vandalism prevention" is 0.4900. This shows that the smart construction site needs further improvement and enhancement in the area of "Machine".

In summary, although the weight of the "Machine" is low, the overall evaluation level of smart construction site safety management can still be improved by enhancing the storage time of construction site data, supporting multiple image signal inputs, reserving more interfaces for future devices, increasing additional measures to prevent theft and vandalism in construction sites [57], and improving the ability of devices to withstand adverse weather conditions.

6.3. Media

"Media" accounts for 0.2959 of the weight and deserves to be considered as a major focus in smart construction site safety management. In the case of "Media", the safety management evaluation level is average (0.5801). As the site environment is more complex than other places, dust, too high or too low temperature, and rainfall will affect the collection and transmission of network data processing [58,59]. Thus, it will largely harm the platform and related software and hardware, resulting in a decline in the security capacity, the stability, and the practicality of smart construction sites. It is also important to have a set of information technology testing equipment and systems that meet the requirements of the site environment where they are located.

"Media" mainly includes "Accuracy of environmental monitoring", "Ability to integrate functions", "Real-time environmental data", and "Richness of monitoring points", with weights of 0.1122, 0.1099, 0.0449, and 0.0289, respectively. "Accuracy of environmental monitoring" requires faster accuracy and recognition speed of environmental factors by the relevant sensors and model systems [60]. This indicator can be a good way to improve the efficiency of the smart construction site in safety management, improve the quality of services, and improve the security capacity of safety. However, it has the lowest evaluation value in the case and needs urgent attention from managers. There is little difference in the number of resilience codes corresponding to the four indicators. The first three indicators with higher weights have evaluation scores between 0.5 and 0.6 in this case, and the scores are not high overall, with small differences. Yet, the lowest weight “Richness of monitoring points” has an excellent evaluation value (0.8333) in this case. The reason for the high evaluation value may be that the smart construction site retains some leeway in the control capacity of the equipment so that new control points can be modified in the system.

Improving the score of the indicators in “Media” can significantly improve the safety management level of smart construction sites. Measures include using high-precision and high-performance equipment [61], increasing the data interfaces of various IoT detection devices, and increasing the types of environmental parameters collected for monitoring.

6.4. Management

“Management” (0.3279) is the most heavily weighted of the four factors, reflecting the emphasis on the need to address management inefficiencies and achieve multi-party collaborative management. The safety management platform of the smart construction site is also a management-based platform, with systems such as schedule, quality, and cost management, to achieve the protection of people, materials, and the environment [62,63]. However, in the case of “Management”, the evaluation score of safety management was average (0.5302). Although current smart construction sites have been more commonly used in information technology, information management for securing the safety of smart construction sites is still not systematic and has been in a fragmented state for a long time, so it is also necessary to strengthen the development and integration of applications related to smart construction site safety management in the future.

The largest weight in “Management” is “Adoption of cloud architecture” (0.1338), followed by “Positioning function” (0.0897), “Early warning and emergency capability” (0.0528), and “Education of employees” (0.0516). This indicates that “Adoption of cloud architecture” is the most important management indicator. Cloud architecture is the use of information technology on the original construction site management infrastructure for different service targets and different project-related parties to expand the architecture and functions of the management platform. By adopting the cloud model, the dynamic situation and data of each aspect of safe construction can be uploaded to the integrated platform in real time to realize the intelligent management of the whole chain and transparent construction, which can support the safety of the smart construction site [64]. In the case of the model application, the indicator scored 0.6667, showing its good performance on the smart construction site. The lowest weight “Education of employees” has the highest evaluation score among management indicators. There is also a certain separation between resilience characteristics and site management measures and weights.

“Positioning function”, which is ranked second in weight, has a resilience code of only 14 and the lowest security score in the case (0.2857). The investigation shows that the smart construction site operation platform can realize the positioning of personnel at the site, as well as the anti-theft and anti-mobile GPS positioning function of materials, combined with the camera. There are two types of positioning functions. In the future, it can provide positioning capability for key machines and real-time positioning for personnel working in deep pits and other dangerous places, so that dangerous situations can be found in time. The indicator “Early warning and emergency capability” with a lower case score (0.4286) can be improved by strengthening the operation of special site equipment and the monitoring and warning measures for the working status of construction personnel [65]. “Education of employees” has the highest score (0.7050) in this smart construction site management indicator. Although the weight is low, the creation of a smart party-building platform system is worth introducing at each smart construction site.

7. Conclusions

With the general trend of digital change in the construction industry, smart construction sites have gradually received attention. In order to improve the safety management capability and promote the sustainable development of smart construction sites, it is urgent to construct a smart construction site safety management evaluation method based on the resilience perspective. Firstly, this research obtained preliminary indicators through 15 policy texts in China by combining two dimensions of 4R resilience characteristics and 4M theory. With the help of a fuzzy interpretive structural model, 15 evaluation indicators were finally determined and the evaluation indicator system of smart construction site safety management was constructed. The weight of each indicator was determined by ANP. The results show that the importance ranking according to experts is management, media, man, and machine, especially the three indicators of person identification, adoption of cloud architecture, and accuracy of environmental monitoring. However, despite the fact that machine has the lowest weight, the analysis of policy texts shows that more resilience measures are used for the safety management of machine. Meanwhile, resilience measures for the three indicators with the highest weights mentioned before are rarely emphasized in policy texts. Due to the deviation between the resilience characteristics and the weights of indicators at present, in the future policy text, it is necessary to refine the content of the indicators of management, media, and man more reasonably, so that the resilience and safety management level of smart construction sites can be improved. Specifically, for example, smart construction sites should consider adding equipment and systems for face recognition, and emphasis should be placed on the accuracy of environmental monitoring equipment and the establishment of a cloud platform for multiple service recipients. Secondly, the evaluation criteria for smart construction site safety management were proposed through standard screening and two rounds of expert consultation. Thirdly, the evaluation model was constructed after determining weights and evaluation criteria. To verify the feasibility of the model, a case study was conducted for analysis. The results of the case study show that the safety management score of the selected case is 0.5995, which corresponds to the safety management level of "average". Safety management capability can be improved by increasing monitoring and warning equipment and emphasizing the positioning of key construction machinery and personnel. Therefore, the model constructed in this research is a valid method to evaluate the current situation of smart construction site safety management. The findings of this research can effectively assess the safety management level, improve the resilience and safety management level of smart construction sites, and thus promote the efficient and green development of smart construction sites.

Although this research has achieved certain results, there are still limitations in the research process. In selecting indicators, it is not possible to use the software to extract indicators from all the policy texts of smart construction sites, as there are too many texts involved. Therefore, the study refers to the theoretical saturation adopted by most scholars as a criterion to end the coding, and there may be some criteria that are not involved.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/buildings13092205/s1. Table S1: Fuzzy correlation matrix of indicators; Table S2: The reachable matrix.

Author Contributions: Conceptualization, H.L. and P.M.; methodology, Y.Q. and X.Z.; software, Y.Q.; validation, Y.Q., H.L. and P.M.; formal analysis, Y.Q.; investigation, Y.Q.; resources, P.M.; data curation, H.L.; writing—original draft preparation, Y.Q.; writing—review and editing, Y.Q., H.L. and X.Z.; visualization, Y.Q.; supervision, P.M.; project administration, P.M.; funding acquisition, P.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China, grant number 72071115.

Data Availability Statement: The data presented in this research are available upon request from the corresponding author. The data are not publicly available due to privacy.

Conflicts of Interest: The authors declare no conflict of interest.

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