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Research on Smart Construction Site Evaluation Model Based on DEMATEL-ANP Method

Jianhu Wang *, Yongjun Qin, Peng He and Wenlong Yan

School of Civil Engineering and Architecture, Xinjiang University, Urumqi 830047, China; qyjjg@xju.edu.cn (Y.Q.); p_he@stu.xju.edu.cn (P.H.); wenlong.yan@xju.edu.cn (W.Y.)
* Correspondence: wangjianhu@xju.edu.cn

Abstract

The current research on smart construction sites is mainly from the perspective of the whole life cycle of the project, and often focuses on the identification of factors at the macro level. It lacks in-depth quantitative analysis of the complex interdependence between influencing factors, and it is difficult to accurately identify key driving factors and weight distribution. This paper takes engineering project management as the perspective, constructs a smart site construction model. The advantages of DEMATEL method and ANP method are innovatively combined to construct the DEMATEL-ANP evaluation model, which overcomes the limitations of single method in weight determination and relationship analysis, and provides a more detailed and scientific analysis framework for the evaluation of smart site construction, and, taking the Urumqi region as an example, its smart construction is evaluated and analyzed. The results of the study show that the correlation between the indicators affecting the construction of smart construction sites is strong, in which the comprehensive influence of personnel safety management, construction quality management, and construction safety management play a greater role, with the comprehensive weights of 0.0917, 0.0817 and 0.0767, respectively; the total score of smart construction site construction of Urumqi region is 63.959, which is in the primary construction stage. Among them, the construction and application of meteorological monitoring are the best, scoring 70.26; the construction and application of most indicators, such as personnel safety management, cost comparison decision-making, dust monitoring, and noise monitoring, are the second best; the construction progress control and wastewater monitoring construction are poor, scoring 55.21 and 57.741. The results of this study can provide direct value to key audiences such as construction enterprise managers, government regulators, and smart site solution providers. This paper considers regions with unique climate types to provide a reference for the construction of intelligent construction sites in the same type of regions.

Keywords: smart construction site; intelligent construction; DEMATEL; ANP method

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1. Introduction

In the trend of digital transformation of the construction industry, 'Smart Construction Site', 'Intelligent Construction' and 'Smart City' are three closely related but different concepts. Smart City is a top-level framework that aims to improve the overall intelligence level of urban governance, services and industries through technologies such as the Internet of Things (IoT), big data, and artificial intelligence (AI) [1]. Intelligent Construction focuses on the construction industry itself, covering the whole industry chain of design, production, construction, operation and maintenance, and uses advanced technologies

such as BIM, robots and automation to realize the intellectualization of building products and processes [2]. The Smart Construction Site is the core landing scene of the intelligent construction concept in the construction stage. It specifically refers to the use of BIM, IoT sensing, AI, cloud computing and other technologies to conduct real-time perception, interconnection, intelligent analysis, collaborative control and decision support for key elements such as 'human, machine, material, method and environment' on the construction site, aiming to improve construction efficiency, safety, quality and environmental management level [3].

The construction industry is foundational in China; however, the conventional construction industry is confronted with challenges, including ineffective management. Despite the advent of novel technological and industrial developments that present opportunities for the construction industry, the issue of "difficult management" persists. In addition, extreme temperature changes (−25 °C to 40 °C) and water shortages (annual precipitation < 300 mm) in the Urumqi region exacerbate the material durability risk and energy-intensive climate control of smart sites, while underestimating such ecological costs under current management models [4]. According to the "14th Five-Year Plan" issued by the Ministry of Housing and Construction in 2022, China's construction industry should continue to improve the efficiency of the construction industry, promote the synergistic development of intelligent construction and new building industrialization as a driving force, and accelerate the pace of transformation and upgrading of the construction industry to a green and low-carbon [5]. Among these technological advancements, the implementation of smart sites has emerged as a pivotal factor in the transformation of the construction industry. The system employs a multifaceted integration of Building Information Modeling (BIM), Artificial Intelligence (AI), and sensing technologies, in conjunction with the Internet of Things (IoT) and the Internet, to achieve a symbiotic relationship between management and construction sites. Currently, maintaining collaboration among members coming from multiple disciplines and organizations has proved problematic [6]. From the perspective of engineering project management, the smart construction site contains advanced management concepts that have the potential to enhance the efficiency of construction management and promote the development and transformation of the construction industry.

The core of the Smart Construction Site is IoT-driven on-site monitoring and optimal management supported by multi-criteria decision making (MCDM). In the following article, in order to facilitate the expression, we will unify the smart site, abbreviated as SCS. Internationally, the application of the Internet of Things in site monitoring is becoming more and more in-depth, involving personnel positioning [7], equipment status monitoring [8], real-time collection of environmental parameters [9], etc., providing a database for SCS. At the level of evaluation methods, MCDM methods, such as AHP, ANP, DEMATEL, TOPSIS, etc., are widely used to solve complex decision-making problems in the construction field. Recent research trends focus on hybrid MCDM models, such as DEMATEL-ANP, DEMATEL-ISM-ANP, to more effectively deal with the interdependence and feedback relationship between evaluation indicators and improve the science and accuracy of evaluation. For example, Benedictus Rahardjo applies DEMATEL-ANP to supply chain risk management [10], and Sumeet Gandhi applies DEMATEL-ISM-ANP to green building assessment [11]. However, the application of DEMATEL-ANP to the evaluation of SCS, especially considering special regional factors, such as the arid continental climate in Urumqi, is still insufficient. Although domestic research has started rapidly, there is still room for improvement in the fineness of the index system and the depth of relationship analysis, and international dialogue needs to be strengthened.

In recent years, scholars have studied the construction of smart construction sites. Tianzi Peng developed an index system to identify the factors impeding the implementation

of smart worksite safety management, categorizing these factors into six levels: technology, economy, organization, cognition, personnel, and environment. Utilizing the DEMATEL-ISM method (ISM method, or Interpretive Structural Modeling) [12], he identified five pivotal factors hindering the integration of information technology for smart worksite safety management. Jiaxin Liu developed a sophisticated worksite system comprising three distinct levels of management, technology, and organization, encompassing 17 components of the smart site system. Utilizing the DEMATEL-ISM method, he systematically categorized these 17 elements into 3 distinct categories. The following elements are to be considered: effect, process, and input [13]. The aforementioned points are supported by Xia et al. [14] A comprehensive analysis was conducted to identify the 17 pivotal factors influencing the development of the smart site. Utilizing the DEMATEL-ISM method, these factors were systematically classified into the impact layer, operation layer, and input layer. This approach offered a quantitative perspective on the anticipated development of the smart site, resources, transformation, and investment. Tengfei Huo [15] identified a total of 23 representative key factors affecting carbon emissions in the construction process, and the DEMATEL-ISM method was used to divide them into 11 causal factors and 12 influencing factors. Among them, the level of economic development, building terminal energy consumption and terminal energy intensity are identified as the three most important factors to help the green upgrade of smart construction sites. Stuart D. Green [16] proposed to conceptualize construction project risk management as a process of discourse competition across multiple organizational areas, and proposed that the issue of self-identity of construction personnel is the core of implementing construction project risk management. Weiguang Jiang [6] proposed a security management system based on a cyber–physical system. Through scene reconstruction design, data perception, data communication and data processing modules, the system establishes synchronous mapping of risk data between virtual construction and physical construction sites.

The present study on smart sites is primarily initiated from the standpoint of the project's entire life cycle, which frequently encompasses numerous domains such as management, technology, and application. The absence of in-depth discourse on the relationship between the influencing factors of smart site construction from a more detailed point of view is likely to result in the phenomenon of insufficient reflection on the importance of a certain level, which will lead to the neglect of the relevant construction. In summary, the existing research has obvious limitations in the evaluation of smart sites:

(1) The evaluation perspective is mostly focused on the whole life cycle of the project or the macro level of technology, management, organization, etc., but there is a lack of in-depth research on the construction of a refined evaluation system from the core dimensions of specific project management, such as safety, quality, schedule, and environment.
(2) In the analysis of factor relationships, although the existing methods can reveal the hierarchical structure, it is difficult to accurately quantify the degree of interaction between factors and their contribution to the final weight distribution.
(3) The evaluation model fails to fully consider the impact of the specific regional environment on the focus of smart site construction.

At the same time, industry practice faces severe challenges. The "14th Five-Year Construction Industry Development Plan" of the Ministry of Housing and Urban–Rural Development clearly requires the improvement of building efficiency and intelligence level. However, in special climate areas such as Urumqi, engineering projects generally face unique problems such as a short construction period, high environmental monitoring requirements, and high safety management pressure. The problem of "difficult management" is particularly prominent. The traditional and universal intelligent site evaluation system is

difficult to accurately guide the construction practice and resource optimization allocation in such areas. Therefore, it is urgent to construct a smart site construction evaluation model that integrates core management dimensions, can quantify the complex dependencies between factors, and adapts to regional characteristics.

2. Construction of an Evaluation Indicator System for Smart Site Construction

From the perspective of project management, this paper constructs a smart site evaluation model through literature analysis and expert interviews. The research in this paper is based on the following key hypotheses:

(1) Indicator measurability and representativeness hypothesis: the 17 secondary indicators, preliminarily screened and finally determined through literature analysis and expert interviews, can fully and effectively characterize the key influencing factors of smart site construction in Urumqi, and these indicators can be measured and evaluated by means of a questionnaire survey.

(2) Method applicability hypothesis: the DEMATEL-ANP method is suitable for analyzing the complex interdependence between the indicators of smart site construction and determining their comprehensive weights. DEMATEL can effectively reveal the causal logic and central position between indicators, and ANP can deal with the feedback dependence between indicators to calculate reasonable weights. The combination of the two can more scientifically reflect the complexity of the smart site system.

(3) Expert and interviewee knowledge reliability hypothesis: experts and construction project managers who participate in interviews and questionnaires have sufficient professional knowledge and practical experience, and their judgments and scores can truly and accurately reflect the relationship between indicators, relative importance and the actual situation of intelligent site construction in Urumqi.

(4) Data validity hypothesis: the valid questionnaire data is reliable and effective, which can be used as the basis for calculating the direct impact matrix, ANP weight and final evaluation score.

Based on the above assumptions, this study analyzes the influence relationship between indicators by the DEMATEL-ANP method, and calculates the comprehensive weight of each index. The Urumqi region is used as an example, and the construction of smart sites in the region is evaluated using the DEMATEL-ANP method. Relevant suggestions are also put forward.

This paper combed the relevant literature, and at the same time, combined the documents and specifications of 16 provincial administrative regions and municipalities directly under the central government, such as Beijing, Guangdong Province, Shanghai, etc., on the evaluation standards of smart construction sites, used VOS Viewer software (VOSviewer1.6.19) to conduct a comprehensive analysis, and preliminarily screened out the key factors that have an impact on the construction of smart construction sites.

According to the findings of the preliminary screening, the present study employed a semi-structured interview method to communicate with experts and construction managers. The objective of this method was to eliminate repetitive or irrelevant factors. The research interests of the experts under consideration herein pertain to the fields of intelligent construction, project management, and construction safety. The construction managers who were interviewed have accumulated more than three years of experience in engineering projects. As a result, the interview data are considered to be both authentic and valid. The factors were filtered according to the answers of the interviewees. For instance, many experts and construction managers thought that cost management involved a wide range

of factors. However, it was most significantly reflected in construction progress. As a result, the factors related to cost management were incorporated into progress management. The evaluation index system of smart construction site construction was constructed based on the results of the interviews. The system encompasses four primary indicators of safety management, quality management, progress management, and environmental management, as well as 17 secondary indicators of personnel safety management, equipment safety management, and construction safety management, as shown in Table 1.

Table 1. Evaluation indicator system for Smart Site Construction.

Tier-1 Indicators	Tier-2 Indicators
Safety Management (A)	Personnel Safety Management (A1) Construction safety management (A2) Equipment safety management (A3)
Quality Management (B)	Intelligent receipt and inspection of materials (B1) Construction quality management (B2) Quality electronic file management (B3)
Progress Management (C)	Cost information collection (C1) Construction cost control (C2) Cost comparison decision-making (C3) Construction progress information collection (C4) Construction progress control (C5)
Environment Management (D)	Sewage Monitoring (D1) Dust Monitoring (D2) Hazardous gas monitoring (D3) Weather Monitoring (D4) Noise Monitoring (D5) Construction Waste Management (D6)

3. Methods

The DEMATEL-ANP method is a comprehensive analysis method that combines the decision-making trial and evaluation laboratory (DEMATEL) method with the analytic network process (ANP) to evaluate the complex interdependence between system factors and determine their relative weights [17]. This integrated structure can solve the decision-making problem of different influence degrees between indicators, and consider the correlation degree and weight of indicators, which solves the shortcomings of the two when they are used alone, and makes the conclusion more scientific and universal.

Decision-Making Trial and Evaluation Laboratory (DEMATEL), alternatively referred to as the Decision-Making Trial and Evaluation Laboratory method, is a system analysis method that was proposed by American scholars Gabus and Fontela in 1971. This method utilizes graph theory as well as matrices as tools [18]. It constructs a direct influence matrix by exploring the relationships between indicators in a system and utilizes the calculation of centrality and causality of each indicator to demonstrate the complex relationships between indicators [19]. Understanding the specific problem and the cluster of intertwined problems can be improved using DEMATEL method, which contributes to the recognition of practicable solutions by a hierarchical structure. This approach, in contrast with the conventional methods, including AHP which assumes the independency of elements, is one of the structural modeling procedures that have the ability to identify the interdependence among the components [20]. However, the weights of each indicator in the DEMATEL method are of equal magnitude, which is inconsistent with reality. To solve this loophole, this paper introduces the ANP method [21] (Analytic Network Process). ANP, or network hierarchy analysis [22], is a novel, practical decision-making method based on AHP and

applicable to non-independent feedback systems proposed by American professor Satty [23] in 1966. The ANP method overcomes the limitation that the indicators are independent of each other in the AHP method and considers that the indicators have a certain connection and influence on each other [24]. In the ANP model, human judgments are integrated for pairwise comparison of the criteria (or sub-criteria) [25]. The networked characteristics of the smart site system determine the interaction dependence of management dimensions such as safety, quality, schedule, and environment. ANP can deal with such feedback loops by constructing a non-hierarchical network structure, making the results more realistic. Although ANP alone can be used to calculate the weight, it cannot distinguish the cause–result factors. DEMATEL accurately reveals the causal role of indicators through centrality (P_i) and causal degree (D_i) to make up for the deficiency of ANP. In comparison with the ISM method previously referenced, the ISM method only generates a hierarchical structure and cannot output weights, but the ANP method has the capacity to present the factor weights through specific data and is not constrained to qualitative relationships between factors. This characteristic renders it more suitable for the identification of significant factors [26]. In addition, the common TOPSIS method is based on the proximity of a limited number of evaluation objects to the idealized target. The method of sorting is to evaluate the relative advantages and disadvantages of the existing objects, which is not suitable for constructing the weight of the evaluation system. In summary, in this paper, the DEMATEL-ANP method is employed to ascertain the relationship between the factors and calculate the comprehensive weights, thereby facilitating the evaluation of the evaluation model of smart site construction.

3.1. Determination of Impact Relationships Among Evaluation Indicators Based on the DEMATEL Methodology

3.1.1. Construct the Direct Impact Matrix D

In this study, a structured questionnaire was employed to assess the relationship between the indicators. The questionnaire design is based on relevant literature and expert interviews to determine the initial index relationship. The detailed contents of the questionnaire are provided in Appendix A. A pre-test (n = 30) was conducted before the questionnaire was issued, and the clarity of expression was optimized according to the feedback. The formal questionnaire uses a clear Likert anchor: the score is 0–4 points, where a score of 0 represents no influence, 1 represents a low degree of influence, 2 represents a fair degree of influence, 3 represents a high degree of influence, and 4 represents a very high degree of influence [27]. After the recovery of the questionnaire, the reliability and validity of the 157 valid questionnaires were tested: the Cronbach's α coefficient was 0.912 (>0.7), indicating that the scale had good internal consistency; the KMO value was 0.873 (>0.7), and the Bartlett spherical test was significant ($p < 0.001$), indicating that the data was suitable for factor analysis and the questionnaire had good structural validity. After passing the inspection, the scores from each questionnaire were arithmetically averaged to obtain the direct impact matrix D, as illustrated in Equation (1).

$$D = \begin{pmatrix} 0 & d_{12} & \dots & d_{1j} \\ d_{21} & 0 & \dots & d_{2j} \\ \vdots & \vdots & \ddots & \vdots \\ d_{i1} & d_{i2} & \dots & 0 \end{pmatrix} \quad (1)$$

where d_{ij} denotes the score of the direct influence of factor i on factor j.

3.1.2. Standardization Directly Affects Matrix X

The direct impact matrix D was standardized according to Equations (2) and (3) with the assistance of SPSSAU software, thereby yielding the standardized direct matrix X.

$$n = min\left(\frac{1}{\max\limits_{1\le i\le n}\sum_{i=1}^{n} d_{ij}}, \frac{1}{\max\limits_{1\le i\le n}\sum_{j=1}^{n} d_{ij}},\right) \tag{2}$$

$$X = nD \tag{3}$$

where n is the scale factor. The scale factor n is the maximum value of the sum of the rows of the direct influence matrix D. This standardization method ensures that all elements of the standardized matrix X are in the range of [0, 1), and the sum of the rows does not exceed 1.

3.1.3. Calculate the Integrated Impact Matrix T

According to Equation (4), the integrated impact matrix T was calculated with the help of SPSSAU software (Version 22.0). The formula is based on the principle of a Markov chain. The element t_{ij} in T represents the sum of the direct and indirect effects of factor i on factor j, that is, the combined effect.

$$T = \sum_{k=1}^{\infty} X^k = X(E - X)^{-1} \tag{4}$$

where $E = \begin{pmatrix} 1 & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & 1 \end{pmatrix}$.

3.1.4. Centrality and Causality Analysis

In the DEMATEL method, the size of the centrality degree is indicative of the strength of the association between the indicator and other indicators in the system. It can be concluded that the larger the centrality degree, the more important the indicator is in the system. The cause degree is employed to gauge the logical relationship between the indicator and other indicators. When the cause degree exceeds 0, it is classified as a cause indicator, signifying that the indicator exerts a more substantial influence on other indicators. Conversely, when the cause degree is less than 0, it is designated as a result indicator, indicating that the indicator is more influenced by other factors [28]. The comprehensive influence matrix T is then subjected to analysis and the centrality $c_i + r_j$ and causality $c_i - r_j$ of each indicator are calculated according to Equations (5) and (6), respectively [29].

$$r_i + c_i = \sum_{j=1}^{n} t_{ij} + \sum_{i=1}^{n} t_{ji} \tag{5}$$

$$r_i - c_i = \sum_{j=1}^{n} t_{ij} - \sum_{i=1}^{n} t_{ji} \tag{6}$$

3.2. Determine the Weights of Each Indicator Based on the ANP Method

3.2.1. Construct Network Structure Model and Judgment Matrix

According to the analysis results of the DEMATEL method, the network structure model is constructed in Super Decisions software (Version 2.10) (hereinafter referred to as SD software) [30], which is an auxiliary software for the network hierarchical analysis method. The ANP questionnaire was also optimized by pre-test (n = 30). The standard

1−9 scale method is used to score the importance. And the scoring rules are shown in Table 2 [31], with a clear anchor point. After screening 134 questionnaires, 106 passed the consistency test (CR < 0.1). The reliability and validity of the 106 valid questionnaires were tested: Cronbach's α coefficient was 0.935; the KMO value was 0.891, and Bartlett's sphericity test was significant ($p < 0.001$). In addition, by calculating the Average Variance Extracted (AVE), the AVE values of each construct (first-level indicator) are greater than 0.5 (safety management: 0.63, quality management: 0.58, schedule management: 0.61, environmental management: 0.55), indicating that the questionnaire has good convergence validity. The judgment matrix is listed, and the data are entered into the SD software according to the scoring results.

Table 2. Rules for scoring the relative importance of indicators.

Score	Meaning	Remarks
1	Both are equally important.	Specifically, a score of −3 indicates that the former is marginally less significant than the latter, while a score of −5 signifies that the former is less important than the latter. A score of −7 denotes that the former is considerably less important than the latter, and a score of −9 indicates that the former is indisputably less important than the latter. The remaining scores correspond to the median values of the rating scale.
3	The former is slightly more important than the latter	
5	The former is more important than the latter	
7	The former is much more important than the latter	
9	The former is definitely more important than the latter	

3.2.2. Calculation of the Weights

SD software was used to test the consistency of each judgment matrix in each questionnaire, also known as the CR test [32]. The judgment matrix is considered to have acceptable consistency, and its data can be used for subsequent analysis of ANP analysis if and only if CR < 0.1. For the questionnaire data that have not passed the test, they should be eliminated or required to be reassessed by experts. After the successful completion of the consistency test, the weighted super matrix B, the limit super matrix L, and the global weights were automatically calculated in the SD software. The weight vector consisting of the global weights of the indicators was noted as W [33].

3.3. Determination of the Combined Weights of the Indicators

According to Equation (7), when combined with the integrated impact matrix T and the weights calculated based on the ANP method W, a mixed weight vector Z can be obtained. Finally, the integrated weights of the indicators can be obtained by normalizing the mixed-weight vector Z.

$$Z = W + T \times W \tag{7}$$

3.4. Classification of Smart Site Evaluation Level

Combining the interaction relationship T between the indicators revealed by DEMATEL with the independent weight W calculated by ANP, a weight Z that considers both the importance of the factor itself and its comprehensive influence in the network is obtained. The evaluation score of smart site construction is calculated according to Equation (8), where is the weight of the ith indicator, is the score of the ith indicator, and S is the total score of the evaluation system.

$$S = \sum_{i=1}^{n} w_i s_i \tag{8}$$

In order to facilitate a more intuitive evaluation of the results, this paper proposes a five-tiered grading system for the assessment of smart site construction, with grades

ranging from 0 to 100. The system is divided into five categories: poor (0–60), ordinary (60–70), good (70–80), excellent (80–90), and outstanding (90–100) [34].

4. Case Study

In this paper, the DEMATEL-ANP method is used to evaluate the smart site construction in the Urumqi region as an example. The sampling of DEMATEL method does not require a large sample size, so it can simplify the correlation analysis process between factors [35]. In this study, 14 representative construction projects under construction in Urumqi were selected as cases. The sample size was determined based on the following considerations:

(1) To meet the DEMATEL-ANP method's demand for expert or manager 's experience judgment data, Hair et al. [36] suggested that the sample size of such studies should be at least 5–10 times the number of indicators. In this study, there are 17 secondary indicators, so the theoretical minimum sample size is 85–170,157 DEMATEL and 106 ANP valid questionnaires meet this requirement;

(2) 14 projects cover different types (8 residential buildings, 4 public buildings, 2 infrastructures), different scales (construction area of 10,000–150,000 m^2) and main contractor types (8 large state-owned enterprises, 4 large private enterprises, 2 local leaders), which can better reflect the diversity of intelligent site construction in Urumqi;

(3) Project selection considers its willingness and basic conditions for applying smart site technology. The 153 project managers interviewed were all from these 14 projects, and all of them had more than 3 years of project management experience and were familiar with the application of smart sites.

In order to ensure the repeatability of the study, the structured questionnaire template used in this study was completely published, as shown in Appendices A and B.

4.1. Determine the Influence Relationship Between Evaluation Indicators

A questionnaire was developed by the smart construction site evaluation index system that was previously outlined, as shown in Figure 1. This system was employed to survey 14 representative construction projects in the Urumqi region. The project types include commercial complexes, transportation hub projects, industrial plants and public hospitals, covering the main types of projects in Urumqi, and the intelligent stage is stratified. Expert interviews and questionnaire respondents cover three core roles, including university intelligent construction researchers, CTO/technical directors of construction enterprises and regulatory experts of government housing and construction departments. All of the experts have practical experience in large-scale projects with industry standards or investments of more than 500 million. A total of 200 questionnaires were disseminated in the course of this survey, and 157 valid questionnaires were recovered, with a recovery rate of 78.5%. Following the mean calculation of the valid scores, the direct influence matrix D of the first-level indicators and second-level indicators was obtained, as demonstrated in Tables 3 and 4.

Table 3. Tier-1 indicators direct impact matrix.

	Safety Management (A)	Quality Management (B)	Progress Management (C)	Environment Management (D)
Safety Management (A)	0	2.75	2.8297	2.3903
Quality Management (B)	2.8191	0	2.8936	2.2566
Progress Management (C)	2.9414	2.8617	0	2.2925
Environment Management (D)	2.6595	2.4308	2.4680	0

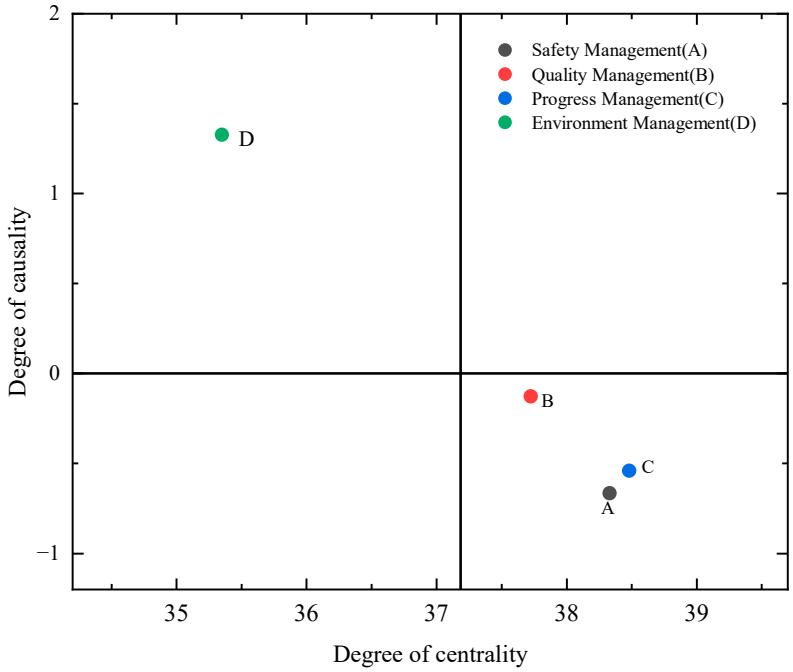


Figure 1. Tier-1 indicator centrality–causality diagram.

Table 4. Tier-2 indicators direct impact matrix.

	A1	A2	A3	B1	B2	B3	C1	C2	C3	C4	C5	D1	D2	D3	D4	D5	D6
A1	0.000	3.198	3.060	2.198	2.698	2.026	2.026	2.319	2.190	2.095	2.379	1.897	2.121	2.078	1.887	1.983	2.217
A2	3.086	0.000	2.905	2.112	2.448	1.948	1.940	2.243	2.172	1.957	2.241	1.966	2.078	2.103	1.862	1.966	2.043
A3	2.922	2.991	0.000	2.026	2.207	1.871	1.845	2.043	1.897	1.802	2.112	1.802	1.793	1.836	1.784	1.845	1.810
B1	2.078	2.129	2.129	0.000	2.078	1.836	1.879	1.983	1.914	1.767	1.940	1.543	1.586	1.681	1.603	1.661	1.670
B2	2.569	2.681	2.500	1.991	0.000	2.129	1.974	2.250	2.103	2.052	2.155	1.698	1.696	1.647	1.552	1.626	1.737
B3	1.930	1.966	1.878	1.826	2.103	0.000	1.853	1.836	1.784	1.750	1.776	1.422	1.457	1.440	1.500	1.552	1.543
C1	1.966	1.983	1.931	1.819	1.862	1.750	0.000	2.164	2.155	1.914	1.957	1.543	1.569	1.526	1.552	1.526	1.560
C2	2.328	2.379	2.310	1.940	2.172	1.793	2.069	0.000	2.216	1.957	2.009	1.672	1.603	1.621	1.517	1.635	1.621
C3	2.060	2.138	2.172	1.897	2.095	1.836	2.000	2.259	0.000	1.914	1.957	1.560	1.543	1.552	1.466	1.526	1.603
C4	2.086	2.095	2.052	1.828	1.957	1.828	1.931	2.043	1.948	0.000	2.060	1.483	1.569	1.491	1.440	1.474	1.569
C5	2.319	2.440	2.379	1.922	2.216	1.828	1.793	2.086	1.983	1.991	0.000	1.560	1.621	1.750	1.543	1.586	1.586
D1	2.026	2.026	1.871	1.621	1.690	1.526	1.578	1.629	1.621	1.517	1.560	0.000	1.474	1.552	1.509	1.422	1.638
D2	2.138	2.130	1.957	1.661	1.687	1.530	1.522	1.583	1.574	1.470	1.487	1.565	0.000	1.923	1.519	1.346	2.192
D3	2.654	2.462	2.135	1.615	1.577	1.365	1.442	1.500	1.462	1.327	1.442	1.500	1.500	0.000	1.481	1.269	1.596
D4	2.327	2.288	2.135	1.577	1.635	1.385	1.481	1.577	1.558	1.538	1.558	1.327	1.692	1.500	0.000	1.440	1.526
D5	2.122	2.078	1.904	1.452	1.574	1.461	1.400	1.478	1.417	1.417	1.478	1.270	1.357	1.357	1.304	0.000	1.172
D6	2.310	2.379	2.207	1.552	1.690	1.655	1.345	1.759	1.759	1.621	1.483	1.414	1.517	1.517	1.310	1.241	0.000

Subsequently, the combined impact matrix T for the primary and secondary indicators was calculated based on Equations (2), (3) and (4), respectively, and is shown in Tables 5 and 6.

Table 5. Tier-1 indicators consolidated impact matrix.

	Safety Management (A)	Quality Management (B)	Progress Management (C)	Environment Management (D)
Safety Management (A)	3.8986	4.0176	4.0754	3.577
Quality Management (B)	4.1515	3.7736	4.0818	3.5693
Progress Management (C)	4.2054	4.0715	3.871	3.6113
Environment Management (D)	3.9784	3.8405	3.8934	3.2187

Table 6. Tier-2 indicators consolidated impact matrix.

	A1	A2	A3	B1	B2	B3	C1	C2	C3	C4	C5	D1	D2	D3	D4	D5	D6
A1	0.279	0.361	0.346	0.278	0.310	0.264	0.266	0.293	0.283	0.268	0.287	0.243	0.255	0.257	0.239	0.244	0.264
A2	0.346	0.273	0.333	0.268	0.296	0.255	0.257	0.284	0.274	0.257	0.276	0.238	0.247	0.250	0.232	0.237	0.252
A3	0.325	0.330	0.244	0.252	0.275	0.240	0.241	0.264	0.254	0.240	0.259	0.222	0.228	0.231	0.218	0.222	0.234
B1	0.280	0.284	0.274	0.182	0.251	0.221	0.224	0.242	0.235	0.221	0.235	0.198	0.205	0.210	0.197	0.201	0.212
B2	0.314	0.320	0.305	0.250	0.218	0.245	0.243	0.268	0.258	0.245	0.259	0.218	0.224	0.225	0.211	0.216	0.231
B3	0.263	0.266	0.255	0.217	0.240	0.164	0.212	0.227	0.220	0.210	0.220	0.186	0.192	0.194	0.185	0.189	0.199
C1	0.272	0.275	0.264	0.224	0.241	0.215	0.172	0.242	0.236	0.221	0.231	0.195	0.201	0.202	0.192	0.194	0.206
C2	0.297	0.301	0.289	0.240	0.263	0.228	0.237	0.201	0.251	0.234	0.246	0.209	0.213	0.216	0.202	0.208	0.219
C3	0.281	0.286	0.276	0.231	0.252	0.222	0.228	0.250	0.187	0.226	0.237	0.200	0.205	0.207	0.194	0.198	0.211
C4	0.276	0.279	0.268	0.225	0.244	0.217	0.222	0.241	0.232	0.173	0.235	0.194	0.202	0.202	0.190	0.193	0.207
C5	0.295	0.301	0.289	0.238	0.262	0.228	0.229	0.253	0.244	0.234	0.193	0.205	0.213	0.218	0.202	0.205	0.217
D1	0.255	0.258	0.245	0.204	0.221	0.195	0.198	0.214	0.208	0.196	0.206	0.142	0.185	0.189	0.178	0.178	0.194
D2	0.265	0.268	0.254	0.211	0.227	0.201	0.202	0.219	0.213	0.201	0.210	0.187	0.153	0.204	0.184	0.181	0.213
D3	0.273	0.271	0.254	0.206	0.220	0.193	0.196	0.212	0.206	0.193	0.205	0.182	0.188	0.151	0.180	0.176	0.195
D4	0.266	0.267	0.255	0.206	0.222	0.194	0.198	0.215	0.209	0.199	0.209	0.179	0.193	0.190	0.142	0.181	0.194
D5	0.243	0.245	0.232	0.189	0.206	0.183	0.183	0.198	0.191	0.183	0.193	0.165	0.172	0.174	0.164	0.132	0.172
D6	0.267	0.272	0.258	0.207	0.225	0.202	0.196	0.221	0.216	0.203	0.209	0.182	0.190	0.192	0.177	0.178	0.156

Next, the centrality and causality of each level 1 and level 2 indicator were calculated using Equations (5) and (6), respectively, as shown in Tables 7 and 8.

Table 7. Degree of centrality and degree of causality of tier-1 indicators.

Tier-1 Indicators	Degree of Centrality	Degree of Causality
Safety Management (A)	38.3305	−0.6638
Quality Management (B)	37.7229	−0.1254
Progress Management (C)	38.4806	−0.5396
Environment Management (D)	35.3467	1.3288

Table 8. Degree of centrality and degree of causality of tier-2 indicators.

Tier-2 Indicators	Degree of Centrality	Degree of Causality
Personnel Safety Management (A1)	9.5339	−0.0621
Construction safety management (A2)	9.4332	−0.2839
Equipment safety management (A3)	8.9227	−0.3634
Intelligent receipt and inspection of materials (B1)	7.6981	0.0452
Construction quality management (B2)	8.4236	0.0772
Quality electronic file management (B3)	7.3037	−0.0258
Cost information collection (C1)	7.4841	0.0795
Construction cost control (C2)	8.0994	0.0086
Cost comparison decision-making (C3)	7.8065	−0.0251
Construction progress information collection (C4)	7.5053	0.0952
Construction progress control (C5)	7.9375	0.1181
Sewage Monitoring (D1)	6.8105	0.1215
Dust Monitoring (D2)	7.0562	0.1270
Hazardous gas monitoring (D3)	7.0146	−0.0106
Weather Monitoring (D4)	6.8055	0.2294
Noise Monitoring (D5)	6.5571	−0.1074
Construction Waste Management (D6)	7.1268	−0.0234

Table 7 shows the centrality and cause degrees of the first-level indicators, in which the centrality degrees of progress management and safety management are 38.4806 and 38.3305, respectively, indicating that these two factors have an important position in the indicator system, which is a key aspect of the current construction of intelligent construction sites in the Urumqi region. Quality management has a slightly lower centrality degree (37.7229),

but its cause degree (−0.1254) is higher than that of progress management (−0.5396) and safety management (−0.6638), which indicates that the construction of quality management of smart construction sites in Urumqi region is relatively independent of the other two management modules and is less influenced by other factors. It should be noted that although the centrality degree of environmental management (35.3467) is the lowest among the four level 1 indicators, its cause degree (1.3288) is the highest, with a higher degree of influence on the other three indicators, which indicates that the Urumqi region has fully considered the environmental management factors in the process of smart construction site construction, which may be since the Urumqi region is located in the inland hinterland with special climatic conditions, and the environmental factors have a significant influence on the other factors have a significant influence. In addition, China's environmental protection efforts have been gradually increasing, and environmental pollution in the construction industry needs to be emphasized. Therefore, environmental management factors can affect the schedule, capital investment, and quality standards.

Table 8 presents the centrality and cause degrees of the secondary indicators. According to the centrality degree, the magnitude of the centrality degree of the three factors in safety management is among the top three among all secondary indicators. The centrality degree of the factor of construction safety management is the largest, with a value of 9.5339, reflecting its importance in the construction of smart sites in Urumqi, which is consistent with the actual situation. However, the cause degree of all three factors in safety management is less than 0, indicating that safety management is primarily influenced by other factors. This suggests that the construction of the safety management module in the construction of smart construction sites in the Urumqi region is not independent, but rather is comprehensively considered about other factors related to safety management. Regarding the degree of cause, the degree of cause of the majority of factors in quality management, progress management, and environmental management is greater than 0, thereby indicating that these factors will have an impact on other factors. Among them, the cause degree of meteorological monitoring in environmental management is the highest at 0.2294, which has the most significant impact on other factors, mainly due to the special climatic conditions in the Urumqi region, with large fluctuations in temperature. This requires focusing on the impact of meteorological indicators on the construction materials, mechanical equipment, etc., of the projects under construction. Consequently, the meteorological monitoring factors exhibit a substantial combined impact, which is consistent with the fundamental nature of environmental management as expressed by the primary indicators.

The centrality–causality diagrams of the first- and second-level indicators are depicted with centrality as the horizontal coordinate and causality as the vertical coordinate, as illustrated in Figures 1 and 2. The centrality–causality diagram is divided into four quadrants, separated by the average value of centrality and line 0. These quadrants are capable of reflecting the relationship between the centrality and causality of different indicators in a comprehensive manner. This approach facilitates a more intuitive understanding of the degree of importance of the indicators and the distinction between cause and result indicators.

As illustrated in Figure 1, safety management, quality management, and progress management are all situated in the fourth quadrant. This suggests that these three factors are of significant importance and are outcome factors, which are susceptible to influence by other factors. By this observation, the secondary indicators contained within these three factors are predominantly distributed in the first and fourth quadrants of Figure 2. Notably, both quadrants are of considerable importance, suggesting that the Urumqi region places significant emphasis on safety, quality, and progress management in the process of constructing smart sites. Furthermore, it employs a comprehensive approach, considering a multitude of factors associated with these three aspects. Conversely, environmental

management is situated in the second quadrant of Figure 1, indicating minimal importance and cause indicators. Its secondary indicators are predominantly exhibited in the second quadrant of Figure 2, suggesting that while environmental management has been comprehensively considered in the development of smart construction sites in the Urumqi region, its significance remains comparatively inferior to that of safety and quality management. This observation aligns with the prevailing circumstances of constructing smart construction sites in Urumqi.

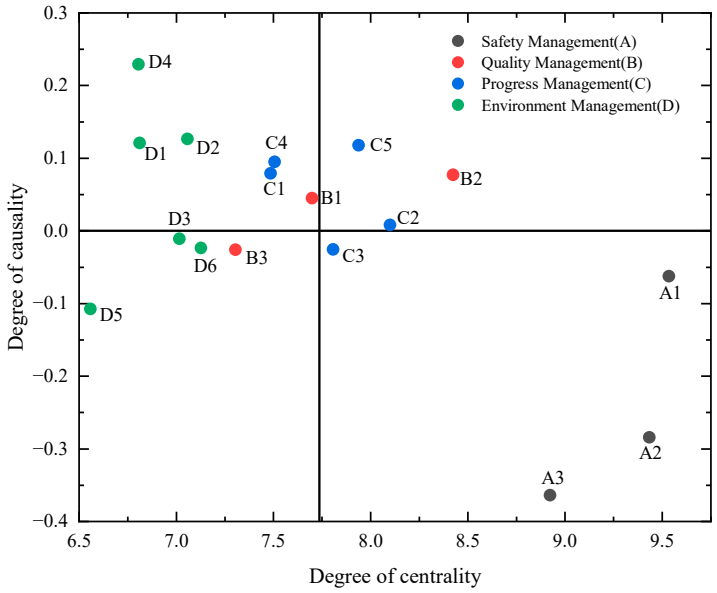


Figure 2. Tier-2 indicator centrality–causality diagram.

The thresholds for dividing quadrants in the figure are the mean value of centrality (the horizontal line) and the value of cause degree 0 (the vertical line). It should be noted that the drawing of the DEMATEL causality diagram depends on the set threshold, and it is necessary to distinguish the cause or result factors. In this study, the cause degree > 0 is defined as the cause factor, 0.1 or <−0.1, which will slightly adjust the position of some indicators in the quadrant, such as the point near the 0 value, but the overall distribution pattern and main conclusions are robust. The core value of the centrality–cause diagram is to intuitively show the relative position and importance of indicators.

4.2. Calculation of Indicator Weights Based on the ANP Method

As demonstrated in Table 1, the results of the DEMATEL analysis, which was utilized to construct the ANP model, and the questionnaire form, which was employed to ascertain the importance of each indicator from the construction project management personnel, are presented. A total of 200 questionnaires were disseminated in the course of the survey, and 134 of them were recovered, yielding a recovery rate of 67%. The collected questionnaire data were subjected to a Confirmatory Factor Analysis (CFA) using Structural Equation Modeling (SEM) resulting in 106 questionnaires meeting the criteria for passing the test. Subsequently, the weighted supermatrix *B*, limit supermatrix *L*, local weights, and global weights of each questionnaire data were calculated by SD software. Finally, the weight of each index in the smart site evaluation system was obtained by calculating the average weight based on the ANP method.

4.3. Calculation of the Combined Weights of the Indicators

According to Equation (6), the combination of the DEMATEL method and the ANP method allows for the calculation of the comprehensive weight W of each index of the

smart site evaluation system. The normalization of W results in the determination of the final comprehensive weight of each index of the smart site evaluation system, as illustrated in Table 9.

Table 9. Comprehensive weight of each indicator of the smart site evaluation system.

Tier-1 Indicators	Comprehensive Weight	Tier-2 Indicators	Comprehensive Weight	Sort
Safety Management	0.2398	Personnel Safety Management	0.0971	1
		Construction safety management	0.0767	3
		Equipment safety management	0.0661	4
Quality Management	0.2092	Intelligent receipt and inspection of materials	0.0647	5
		Construction quality management	0.0817	2
		Quality electronic file management	0.0628	6
Progress Management	0.2709	Cost information collection	0.0546	8
		Construction cost control	0.0555	7
		Cost comparison decision-making	0.054	10
		Construction progress information collection	0.0524	11
		Construction progress control	0.0545	9
Environment Management	0.2343	Sewage Monitoring	0.0458	16
		Dust Monitoring	0.0473	14
		Hazardous gas monitoring	0.0503	12
		Weather Monitoring	0.0477	13
		Noise Monitoring	0.0426	17
		Construction Waste Management	0.0465	15

As illustrated in Table 9, the aggregate weights of the primary and secondary indicators are presented. Among the primary indicators, progress management exhibits the most significant combined weight of 0.2709, signifying that the Urumqi region places considerable emphasis on the oversight of construction progress. This might be attributable to the deferral of the project due to the Xinguan epidemic. Consequently, following the resumption of operations, the Urumqi region's smart construction site platform prioritizes the management of progress control and elucidates the rationale behind the inclusion of a more extensive array of secondary indicators within the filtered progress management module. Furthermore, concerning the aggregate weight of the primary indicators, safety management (0.2398) exhibits a marginal superiority over environmental management (0.2343). However, the number of secondary indicators incorporated into safety management is merely half of that encompassed by environmental management. Nonetheless, the combined weights are prioritized higher, thereby signifying that the Urumqi region has consistently accorded paramount significance to the safety management of the project in the construction of the smart site.

It is noteworthy that the comprehensive weight of quality management is only 0.2092, which is lower than that of environmental management. This finding contradicts the prevailing perception, but it does not imply that quality management is of low importance. As demonstrated in Table 9, the secondary indicators incorporated within the framework of quality management emerge as the foremost contributors to the comprehensive evaluation. A prime illustration of this is the integrated weight of construction quality management, which achieves a noteworthy ranking of 0.0817 and occupies the second position among all secondary indicators. Consequently, the modest comprehensive weight of quality management can be attributed to the relatively limited number of secondary indicators, suggesting that the development of smart construction sites in Urumqi necessitates a more profound optimization of the quality management module's content. Moreover, in light of China's ongoing commitment to environmental protection, the adoption of green, low-

carbon, and other sustainable development concepts has been a persistent feature of its economic and social agenda. This commitment is also evident in the construction sector, particularly in the context of smart construction sites in the Urumqi region. These sites have demonstrated a notable emphasis on environmental management, as evidenced by the increased number of secondary indicators. This phenomenon, as discussed in the preceding section, elucidates the preeminence of environmental management in the region.

4.4. Evaluation and Suggestions on Smart Site Construction in the Urumqi Region

In this study, control and scoring items are set apart according to the meaning of each secondary indicator, and the questionnaire is designed based on this. The scoring of the indicator is contingent upon the satisfaction of all the control items of the indicator; if the indicator is not satisfied, it is assigned a value of 0 points. A questionnaire survey was conducted on construction projects in the Urumqi region. The survey targeted the management personnel of the respective projects. A total of 200 questionnaires were distributed, and 153 were returned, yielding a recovery rate of 76.5%. The average score of the questionnaire was calculated using Formula (8), resulting in a total score of 63.959 points for the construction of the smart site in the Urumqi region, indicating an ordinary level of performance. The score of each indicator is shown in Table 10a.

Table 10. (**a**) Urumqi smart site construction indicator score. (**b**) Example of correlation between evaluation score and project performance index.

(a)

Tier-1 Indicators	Tier-2 Indicators	Tier-2 Indicator Score	Tier-2 Indicator Comprehensive Weight	Tier-1 Indicator Score	Total Score
Safety Management	Personnel Safety Management	67.309	0.0971	15.5345	63.983
	Construction safety management	62.502	0.0767		
	Equipment safety management	63.614	0.0661		
Quality Management	Intelligent receipt and inspection of materials	62.185	0.0647	13.096	
	Construction quality management	63.518	0.0817		
	Quality electronic file management	61.765	0.0628		
Progress Management	Cost information collection	64.61	0.0546	17.0732	
	Construction cost control	63.174	0.0555		
	Cost comparison decision-making	67.993	0.054		
	Construction progress information collection	64.096	0.0524		
	Construction progress control	55.214	0.0545		
Environment Management	Sewage Monitoring	57.741	0.0458	18.2793	
	Dust Monitoring	67.435	0.0473		
	Hazardous gas monitoring	66.134	0.0503		
	Weather Monitoring	70.26	0.0477		
	Noise Monitoring	67.453	0.0426		
	Construction Waste Management	62.231	0.0465		

Table 10. *Cont.*

(b)			
Project	**Intelligent Site Evaluation Score**	**Key Performance Indicators**	**Relevance Observation**
A	68.2	Safety accident rate: 0.12 times/million man-hours (industry average: 0.25) Progress deviation: +2.1% (excellent) The number of sewage discharges exceeding the standard: 0 times	The overall score is high, close to good, and its safety management and environmental management scores are outstanding, which is consistent with the actual excellent safety and environmental performance. The progress control score is medium, corresponding to slight progress deviation.
B	58.7	Safety accident rate: 0.38 times/million working hours (higher) Progress deviation: −15.3% (serious lag) Dust complaints: 3 times	The overall score is low and close to the poor level. The scores of construction safety management, construction schedule control and dust monitoring are significantly lower than the average level, which directly corresponds to the high accident rate, serious schedule lag and dust complaints.

As illustrated in Table 10a, the implementation of smart sites in the Urumqi region appears to be in its nascent stages, with most sites still in the primary construction phase. Specifically, the construction and application of weather monitoring demonstrated the highest level of proficiency, with a rating of 70.26, reaching a commendable level of performance. The construction and application of most indicators, such as personnel safety management, cost comparison decision-making, dust monitoring, and noise monitoring, are suboptimal, with ratings between 60 and 70, which is at an ordinary level. There is considerable room for improvement. However, the ratings for construction progress control and sewage monitoring both fall below 60 points, indicating substandard construction and the need for significant enhancement.

In order to preliminarily verify the predictive validity of the evaluation model, we selected two typical projects involved in the evaluation, Project A: large commercial complex; project B: municipal bridge engineering, the correlation analysis between its intelligent site evaluation score and key performance indicators (KPI) is carried out, and the results are shown in Table 10b.

Although limited by sample size and data acquisition, the above cases preliminarily show that there is a strong correlation between the score of this evaluation model and the actual performance of the project in terms of safety record, schedule control and environmental compliance. The model has certain predictive ability and practical guidance value. Future research can further verify the predictive validity of the model through larger samples of longitudinal data.

Consequently, this paper proposes the following recommendations to enhance the development of smart construction sites in Urumqi:

(1) Optimize the management module. The results of interviews with experts and construction managers in the Urumqi region indicate that cost management and material management are merged into progress management and quality management, respectively. This suggests that the current management modules of smart site construction in the region are deficient and require optimization. Consequently, in the subsequent phase of smart site construction, the Urumqi region must prioritize the optimization of management modules, encompassing cost management, material management, technology management, and video monitoring management.

(2) In-depth consideration of the influencing factors contained in the different management modules. A number of the management modules in this paper contain a reduced number of influencing factors. For example, safety management and quality manage-

ment each contain only three relevant influencing factors. Consequently, the Urumqi region must give further consideration to the factors affecting different management modules to enhance the smart site management system.

(3) Accelerating the construction of supporting facilities related to smart construction sites. The data presented in Table 9 indicates that certain indicators possess elevated comprehensive weights yet receive low ratings, including construction safety management and construction quality management. This finding suggests that the supporting facilities related to the construction of smart construction sites in the region are not optimal, contributing to the low ratings observed. Consequently, in the future construction and development of smart construction sites, the Urumqi region must expedite the construction of relevant supporting facilities, such as sensing equipment and the Internet of Things. Furthermore, it is imperative to take into account the organic unity of smart construction sites from the perspectives of supervision (government agencies), enterprise (business units), and project (construction sites). This approach is essential for dismantling the "end-to-end" information barriers and the "information island" phenomenon. By doing so, we can establish a comprehensive smart construction site ecosystem.

Based on the above recommendations, Table 11 refines the key action items and investment priorities for the main implementers.

Table 11. Smart site construction promotes key action items and investment priorities.

Implementing Subject	Key Action Items	Attention Priority
Contractor	(1) Purchasing and deploying an integrated intelligent site management platform, focusing on strengthening progress control and material management modules.	High
	(2) Increase the deployment density of intelligent sensor equipment in the construction area, especially at the sewage discharge point and the key working surface.	High
	(3) Develop or introduce BIM-based construction schedule simulation and dynamic control tools.	Medium-high
	(4) Establish a smart site data center to open up data barriers within the project side and with the enterprise side.	Medium-high
Departments of Supervision	(1) Develop and implement local standards/guidelines for the construction and evaluation of smart sites that adapt to the characteristics of Urumqi.	High
	(2) Establish special funds or provide tax incentives to encourage enterprises to invest in smart site supporting equipment, especially environmental monitoring and safety management equipment.	High
	(3) Build a regional-level smart site supervision platform to achieve unified access and supervision of key project data.	Medium-high
	(4) Organize the exchange and training of smart site best practices to improve the overall application level of the industry.	Medium

Table 11. *Cont.*

Implementing Subject	Key Action Items	Attention Priority
Project Management Department	(1) Optimize the application process of the smart site system to ensure that the cost and material data are accurately collected in real time and applied to schedule decisions.	High
	(2) Strengthen the application depth of the construction progress control module, and incorporate the intelligent early warning of planned and actual progress deviations into daily management.	High
	(3) Regular inspection and maintenance of sewage, dust, noise and other environmental monitoring equipment to ensure data validity.	Medium-high

5. Conclusions

From the perspective of engineering project management, this paper constructs a smart site evaluation model through a combination of literature analysis and expert interviews. For cities with a similar climate, such as Lanzhou, Xining and other cities, this evaluation model can be directly adopted. Only local data need to be combined to generate customized weights, such as adjusting meteorological monitoring weights, so as to increase the pertinence of the model and avoid repeated modeling costs. For the development of the national construction industry, the strategic position of 'environmental management' in the smart site system is verified, and the need to prioritize the deployment of environmental monitoring modules in areas with relatively strict environmental policies is prompted.

The DEMATEL-ANP method was employed to analyze the influence relationship between indicators, calculate the comprehensive weight of each indicator, and evaluate the construction of smart construction sites in the Urumqi region. The results indicate that the construction of smart construction sites in the Urumqi region is in the primary stage and has significant potential for improvement.

Future research could start from the following aspects:

(1) The project management indicators examined in this paper are limited to four primary domains: safety, quality, progress, and environment. Future research has the potential to expand the evaluation indicators and refine the evaluation model, thereby enhancing its robustness.
(2) Future research endeavors may encompass the development of a dynamic evaluation model that exhibits temporal variability, with a focus on investigating the most salient influencing factors that undergo change over time.
(3) Subsequent research endeavors may encompass the exploration of the mediating role between disparate factors. This exploration would facilitate the acquisition of insight into the interactions between factors, the identification of pivotal mediating factors, and the revelation of the influencing mechanisms of different factors on the construction of smart construction sites.
(4) In this paper, the unique climate type and development of the Urumqi region are particularly taken into account to provide a reference for the construction of smart sites in similar regions and to further promote the development of smart sites.
(5) Increasing cross-regional verification, replicating research in typical regional cities such as hot and humid Guangzhou and high altitude, and constructing a regional adaptation map of China's smart construction sites.

(6) Standard interfaces are defined between modules to promote the interaction between different digital systems, such as ERP, BIM, and IoT sensors, and common standards are adopted between companies, control agencies, and project sites.

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Institutional Review Board Statement: All participants were fully informed about the purpose of the research, the use of their data, the assurance of anonymity, and that there were no foreseeable risks associated with their participation.

Informed Consent Statement: Informed consent was obtained from all participants involved in the study. Due to the minimal risk nature of this survey research, verbal informed consent was obtained prior to the administration of the questionnaire.

Data Availability Statement: All data generated and analyzed during this study are included in this article.

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

Appendix A. DEMATEL Indicator Relationship Questionnaire

In the form of 'n × n' matrix, experts are required to score the degree of influence of row index 'i' on column index 'j' by 0–4 points (anchor point: 0 = no influence, 1 = weak influence, 2 = medium influence, 3 = strong influence, 4 = strong influence).

1. Safety Management

(1) Personnel Safety Management

No.	Construction Content	Suitable	Not Suitable	Delete	Revision Suggestions
Control Items					
1	Intelligent access control system, achieving intelligent information identification of employees	☐	☐	☐	
2	Intelligent on-site personnel safety management, timely avoidance of personnel risks	☐	☐	☐	
Scoring Items					
1	Intelligent verification of identity information of entering personnel, automatic attendance recording	☐	☐	☐	
2	Automatic detection of alcohol content of entering workers, warning issued if content exceeds limit	☐	☐	☐	
3	Automatic blood pressure detection of entering workers, reminder issued if blood pressure is too high	☐	☐	☐	

No.	Construction Content	Suitable	Not Suitable	Delete	Revision Suggestions
Scoring Items					
4	Automatic identification of on-site personnel wearing safety equipment, warning issued to personnel not wearing safety equipment	☐	☐	☐	
5	Intelligent monitoring of on-site personnel movement and location, automatic identification of safety status	☐	☐	☐	
6	Automatic identification of unauthorized personnel intrusion, standardizing safety management in construction areas	☐	☐	☐	
7	Intelligent identification of removal or absence of safety barriers on construction site, and issuance of warnings	☐	☐	☐	
8	Intelligent reminders for safety education, using VR and other intelligent equipment for personnel safety education	☐	☐	☐	
9	Digital simulation of safe evacuation routes, inspecting the layout of safe evacuation routes in construction site living and office areas	☐	☐	☐	
10	Use of other information technology means or intelligent equipment to improve personnel safety management level	☐	☐	☐	

(2) Epidemic Prevention Safety Management

No.	Construction Content	Suitable	Not Suitable	Delete	Revision Suggestions
Control Items					
1	Intelligent epidemic prevention system: Use information technology to manage epidemic information and risk collection	☐	☐	☐	
Scoring Items					
1	Intelligent identification of body temperature of entering personnel, prompt and warning for individuals with abnormal temperature	☐	☐	☐	
2	Intelligent checking of nucleic acid test codes, health QR codes, travel history QR codes	☐	☐	☐	
3	On-site intelligent identification of mask wearing, warning issued for personnel not wearing masks	☐	☐	☐	
4	Intelligent reminders for scheduled disinfection	☐	☐	☐	

No.	Construction Content	Suitable	Not Suitable	Delete	Revision Suggestions
Scoring Items					
5	Real-time sharing of epidemic information, improving epidemiological investigation efficiency	☐	☐	☐	
6	On-site display of recent epidemic risks and all historical risk records	☐	☐	☐	
7	Use of other information technology means or intelligent equipment to improve epidemic prevention safety management level	☐	☐	☐	

(3) Construction Process Management

No.	Construction Content	Suitable	Not Suitable	Delete	Revision Suggestions
Control Items					
1	Data collection: Real-time monitoring of construction processes, achieving data visualization, and centralized management of information, recorded and uploaded to cloud	☐	☐	☐	
2	Intelligent warning prompts: Intelligent analysis and judgment, providing warning prompts to avoid safety accidents.	☐	☐	☐	
Scoring Items					
1	Visual data capability: Using smart construction site platform to visually display real-time conditions and hazard distribution of scaffolding, shafts, high-formwork, foundation pits, etc.	☐	☐	☐	
2	Real-time monitoring of horizontal displacement and settlement of shafts, exceeding limits warning, danger alarm	☐	☐	☐	
3	Scaffolding intelligent monitoring: Monitoring pipe diameter, horizontal/vertical spacing, step distance, height, etc., of external building scaffolding; intelligent identification of hazard points, early warning	☐	☐	☐	
4	Use of other information technology means or intelligent equipment to improve construction process management level	☐	☐	☐	

(4) Equipment Safety Management

No.	Construction Content	Suitable	Not Suitable	Delete	Revision Suggestions
Control Items					
1	Smart equipment management platform: Real-time monitoring, achieving data visualization, centralized information management	☐	☐	☐	
2	Intelligent warning prompts: Intelligent analysis and judgment, safety detection, providing warning prompts to avoid safety accidents	☐	☐	☐	
Scoring Items					
1	Intelligent collection of maintenance information for project equipment and work machinery, timely uploading of data to management platform	☐	☐	☐	
2	Smart sensing: Using positioning technology to monitor equipment operating status	☐	☐	☐	
3	Smart equipment management platform, enabling visualization of equipment data, safety status, and maintenance status.	☐	☐	☐	
4	Automatic monitoring of construction elevator operation: Monitoring load capacity, top/bottom impact, front/rear door and skylight switch status, running speed, number of people in cage; providing prompt warnings	☐	☐	☐	
5	Automatic monitoring of tower crane safety: Intelligent focusing on surrounding environment, real-time shooting, expanding operator's field of view	☐	☐	☐	
6	Automatic prevention of multi-tower collision; tower crane hook visualization, reducing hidden dangers like blind lifting operations	☐	☐	☐	
7	Welder safety control, including but not limited to monitoring of current, power supply, effective running time, idle time	☐	☐	☐	
8	Intelligent maintenance reminders. Warning for equipment not maintained on time, and prohibition of use	☐	☐	☐	
9	Intelligent identification of safety hazards, e.g., equipment overload, equipment maintenance status, avoiding safety accidents	☐	☐	☐	
10	Use of other information technology means or intelligent equipment to improve equipment safety management level	☐	☐	☐	

2. Quality Management
(1) Intelligent Material Receiving and Inspection

No.	Construction Content	Suitable	Not Suitable	Delete	Revision Suggestions
Control Items					
1	Intelligent weighing: Automatic calculation of cargo weight (quantity), intelligent collection of videos, photos and other image data, uploaded to system database	☐	☐	☐	
Scoring Items					
1	Automatic alarm: When the planned quantity of materials entering the site does not match the actual quantity, the system can perform comparative analysis and automatically alarm	☐	☐	☐	
2	Supplier screening: Automatically rank suppliers with large material supply deviations, helping enterprises select high-quality suppliers.	☐	☐	☐	
3	Use of other information technology means or intelligent equipment to improve on-site material receiving and inspection management level	☐	☐	☐	

(2) Quality Inspection and Testing

No.	Construction Content	Suitable	Not Suitable	Delete	Revision Suggestions
Control Items					
1	Process quality control: For on-site witness sampling, including but not limited to recording and retention of sampling process, detection data statistics, query, analysis and warning functions	☐	☐	☐	
2	Quality acceptance: Information technology should be used for the management function of quality acceptance at key nodes and for sub-divisional works of construction projects	☐	☐	☐	
Scoring Items					
1	Use of AI recognition, control tracking, positioning measurement, 3D scanning, time-lapse photography, drone applications, 5G + AI remote video precise measurement and other technologies to achieve remote visual actual measurement, realizing tool intelligence and process digitization.	☐	☐	☐	
2	Digital pile foundation monitoring: Collecting original data during construction to assist operators in precise construction, improving pile qualification rate and production efficiency.	☐	☐	☐	

No.	Construction Content	Suitable	Not Suitable	Delete	Revision Suggestions
Scoring Items					
3	On-site mass concrete monitoring: Including but not limited to, automatic temperature collection for mass and winter concrete, wireless transmission of collected temperatures, real-time viewing of mass and winter concrete temperatures via PC/mobile devices, data resumption after power failure for mass and winter concrete temperature measurement, temperature exceeding limit warning, temperature measurement record statistics and analysis.	☐	☐	☐	
4	On-site standard curing lab concrete monitoring: Automatic constant temperature and humidity control in on-site standard curing labs, recording of curing logs in on-site standard curing labs, temperature and humidity alarm for on-site standard curing labs, real-time collection of temperature and humidity data in on-site standard curing labs, remote video monitoring of on-site standard curing labs.	☐	☐	☐	
5	Embedded component and axis deviation monitoring: Remote video measurement of deviation between embedded components and axes, comparing with construction electronic drawings, remote verification of whether embedded components are offset.	☐	☐	☐	
6	Using handheld devices to inspect specific sub-divisional works, filling in inspection data, taking photos of the inspection site and uploading them	☐	☐	☐	
7	Quality evaluation: Automatic generation and pushing of rectification notices	☐	☐	☐	
8	Rectification feedback, and real-time viewing of rectification completion status via intelligent means	☐	☐	☐	
9	Use of other information technology means or intelligent equipment to improve on-site quality inspection and testing level	☐	☐	☐	

(3) Quality Electronic Archive Management

No.	Construction Content	Suitable	Not Suitable	Delete	Revision Suggestions
Control Items					
1	Collection, recording, statistical analysis, query and warning of key project quality control documents.	☐	☐	☐	
2	Associating quality data with BIM models and providing automatic filing function for digital archives	☐	☐	☐	
Scoring Items					
1	CA certification, electronic signature, and paperless work	☐	☐	☐	
2	QR codes or other electronic tags: Using QR codes or other IoT electronic tag technologies on-site, enabling project team members and external visitors to more conveniently access relevant engineering information	☐	☐	☐	
3	Quality mock-up: Creating targeted virtual quality mock-ups based on actual project conditions, including but not limited to mock-up type, construction process, main content, picture examples, defect types and handling measures, etc.	☐	☐	☐	
4	Use of other information technology means or intelligent equipment to improve quality electronic archive management level	☐	☐	☐	

(4) Prefabricated Building Quality Management

No.	Construction Content	Suitable	Not Suitable	Delete	Revision Suggestions
Control Items					
1	Use of information technology for quality management of prefabricated buildings	☐	☐	☐	
Scoring Items					
1	Introducing information technology in the prefabricated component production design phase to improve component quality and precision	☐	☐	☐	
2	Using information technology for construction simulation before formal assembly, verifying the rationality of component lifting sequences, improving construction quality	☐	☐	☐	

No.	Construction Content	Suitable	Not Suitable	Delete	Revision Suggestions
Scoring Items					
3	Prefabricated building floor flatness monitoring	☐	☐	☐	
4	Using information technology for comprehensive MEP adjustment, standardizing the splitting, design, and industrial production of various MEP pipeline and equipment modules	☐	☐	☐	
5	Applying QR code or RFID technology, setting electronic tags in prefabricated components to track and monitor production, transportation, and assembly status in real time	☐	☐	☐	
6	Use of other information technology means or intelligent equipment to improve prefabricated construction quality level	☐	☐	☐	

3. Schedule Management
(1) Cost Information Collection

No.	Construction Content	Suitable	Not Suitable	Delete	Revision Suggestions
Control Items					
1	Collection and analysis: Intelligent collection of cost information, statistical analysis of material entry status	☐	☐	☐	
Scoring Items					
1	Terrain analysis for earthwork excavation and backfilling calculation, determining machinery and material transportation routes	☐	☐	☐	
2	Intelligent material management system: Using multiple weighing platforms with data collection terminals to statistically analyze material entry status, accurately grasping supply deviations in real-time	☐	☐	☐	
3	Online material procurement and ordering; managers inventory and inspect materials upon entry, record ledgers and upload to cloud platform; using internet management to facilitate querying material in/out status, showing management traces, facilitating settlement	☐	☐	☐	
4	Using drone technology to collect data and transmit to smart construction site cloud platform for cost control	☐	☐	☐	
5	Other intelligent equipment or information technology means for cost information collection	☐	☐	☐	

(2) Construction Cost Control

No.	Construction Content	Suitable	Not Suitable	Delete	Revision Suggestions
Control Items					
1	Cost information determination: Accurately determining the construction cost of each process based on construction progress	☐	☐	☐	
2	Cost information control: Enabling construction units to intuitively understand the cost management status of the project at various stages	☐	☐	☐	
Scoring Items					
1	Establishing an information-based design platform for scheme collaboration on construction planning, funds, and materials, providing reference for subsequent construction schedule collaboration framework	☐	☐	☐	
2	Using 3D design technology to improve the accuracy of material, equipment, and construction quantity bidding, constraining design errors within reasonable limits	☐	☐	☐	
3	Adopting BIM 5D management mode to effectively control process, method, and construction cutting cost-related coefficients, visualizing management of contract funds and costs during construction, achieving material control	☐	☐	☐	
4	Automatic statistics of engineering quantities through input of actual building information in BIM models, generating cost information reports through the platform	☐	☐	☐	
5	Other intelligent equipment or information technology means for construction cost control	☐	☐	☐	

(3) Cost Comparison and Decision-making

No.	Construction Content	Suitable	Not Suitable	Delete	Revision Suggestions
Control Items					
1	Data comparison and optimization: Intelligent comparative analysis of actual collected data with model data, optimizing fund usage, minimizing project costs	☐	☐	☐	

No.	Construction Content	Suitable	Not Suitable	Delete	Revision Suggestions
Scoring Items					
1	5D cost management mode: Effectively performing cost comparison and control during construction management, adopting more reasonable construction techniques to control costs	☐	☐	☐	
2	Cost control automatic optimization system: Optimizing fund usage, automatically optimizing the planning, design, construction, operation, and maintenance costs of the project to reduce construction costs	☐	☐	☐	
3	Other intelligent equipment or information technology means for cost comparison and decision-making	☐	☐	☐	

(4) Construction Schedule Information Collection

No.	Construction Content	Suitable	Not Suitable	Delete	Revision Suggestions
Control Items					
1	Construction schedule information control: Collecting on-site progress for each period and work area, dynamically viewing overall project video monitoring in real time, and timely uploading collected data to management platform	☐	☐	☐	
Scoring Items					
1	Conducting drone aerial photography of overall construction progress, capturing visual progress of each period and work area, assisting project site layout and work area coordination	☐	☐	☐	
2	Using sensor devices instead of manual labor to effectively perceive construction data such as temperature and stress in complex and changing on-site environments	☐	☐	☐	
3	Using electronic maps and video tracking technology to establish real-time visual, seamless communication between remote locations and site, incorporating instant meetings for remote real-time monitoring of site work	☐	☐	☐	
4	Installing time-lapse photography equipment on the construction site to record on-site construction conditions	☐	☐	☐	

No.	Construction Content	Suitable	Not Suitable	Delete	Revision Suggestions
Scoring Items					
5	In the smart construction site management platform, project data is uploaded to the cloud management system in real time for data analysis. All project participants can access relevant site information online in real time via the cloud, completing multiple cloud applications like project schedule coordination and resource allocation, achieving multi-party collaborative work.	☐	☐	☐	
6	Other intelligent equipment or information technology means for construction schedule information collection	☐	☐	☐	

(5) Construction Schedule Control

No.	Construction Content	Suitable	Not Suitable	Delete	Revision Suggestions
Control Items					
1	Digital construction schedule simulation: Virtual simulation of construction processes after collecting actual work efficiency of various trades	☐	☐	☐	
2	Digital warning of deviations: Intelligent identification of deviations between simulated schedule and actual progress, real-time warning of schedule deviations and proposing optimization solutions	☐	☐	☐	
Scoring Items					
1	Reviewing construction drawings based on BIM models, efficiently completing drawing reviews	☐	☐	☐	
2	Using BIM technology for spatial simulation of construction excavation, making technical briefings concise and intuitive	☐	☐	☐	
3	Fully simulating the real construction scene of the site in 3D dynamic form based on BIM models, obtaining realistic experience through VR	☐	☐	☐	
4	Using drones to collect control points and elevation information, matching with BIM 3D models for similarity analysis, achieving automated aerial photography, modeling, 3D model similarity matching, providing comprehensive visual data expression for construction progress	☐	☐	☐	

No.	Construction Content	Suitable	Not Suitable	Delete	Revision Suggestions
Scoring Items					
5	Combining laser point cloud scanning technology and BIM technology to obtain geometric information of internal building space and generate point cloud models, inputting them into the digital information platform, comparing with BIM models to generate dimensional deviation reports between physical structure and BIM model	☐	☐	☐	
6	Innovatively integrating BIM 4D technology with databases to construct a construction schedule information database for schedule optimization, virtual construction, actual progress acquisition, and recording of abnormal problems	☐	☐	☐	
7	Placing the reporting content of each project phase in a centralized platform, automatically collecting operational data for that phase to improve progress report generation efficiency; using BIM to connect different software to acquire and process project information in real time at various stages	☐	☐	☐	
8	Tracking rectification progress in real time via mobile APP one-click photos, voice, and short video auto-upload	☐	☐	☐	
9	Setting time intervals for time-lapse photography, automatically recording into short videos	☐	☐	☐	
10	Other intelligent equipment or information technology means for construction schedule control	☐	☐	☐	

4. Environmental Management
(1) Wastewater Monitoring

No.	Construction Content	Suitable	Not Suitable	Delete	Revision Suggestions
Control Items					
1	Achieving intelligent monitoring and information management of wastewater discharge at the construction site	☐	☐	☐	
Scoring Items					
1	Intelligent warning: Intelligent collection of domestic wastewater discharge data, automatic warning prompts when data reaches threshold	☐	☐	☐	

No.	Construction Content	Suitable	Not Suitable	Delete	Revision Suggestions
Scoring Items					
2	Adding monitoring points for groundwater in exploited aquifers: If shallow groundwater is already contaminated and downstream drinking water sources exist, better prevention of further pollution by adding monitoring points for exploited groundwater	☐	☐	☐	
3	Automatic calibration and equipment fault alarm function: Wastewater monitoring equipment has automatic calibration function; automatic alarm when equipment faults cannot be repaired by calibration	☐	☐	☐	
4	Use of other information technology means or intelligent equipment to improve on-site wastewater management level	☐	☐	☐	

(2) Dust Monitoring

No.	Construction Content	Suitable	Not Suitable	Delete	Revision Suggestions
Control Items					
1	Dust automatic monitoring: Using information technology to intelligently monitor dust pollution on-site and surrounding areas	☐	☐	☐	
2	Dust control system: When dust data exceeds threshold, system automatically initiates control measures	☐	☐	☐	
Scoring Items					
1	Intelligent warning: Automatic collection of dust data on-site and surrounding areas, automatic warning when data reaches threshold	☐	☐	☐	
2	Dust monitoring points should be set in key areas within the camera surveillance range of the construction site, with real-time display function	☐	☐	☐	
3	Intelligent mist cannon system: When dust data exceeds	☐	☐	☐	

Appendix B. ANP Index Importance Questionnaire

Rating options: 1 (equally important) to 9 (absolutely important), the reciprocal of 1/3/5/7/9 indicates opposite importance.

(1) Cost Information Collection

No.	Construction Content
Control Items	
1	Collection and Analysis: Intelligently collect cost information, statistically analyze material arrival status
Scoring Items	
1	Terrain analysis for earthwork excavation/backfill calculation, determining machinery and material transportation routes
2	Intelligent material management system: Utilize multiple weighing platforms with data collection terminals to statistically analyze material arrival status, accurately grasping supply deviations in real time
3	Online material procurement and ordering; managers inventory and inspect materials upon arrival, record ledgers and upload to cloud platform; use internet management to facilitate querying material in/out status, showing management traces, facilitating settlement
4	Use drone technology to collect data and transmit to the smart construction site cloud platform for cost control
5	Other intelligent equipment or information technology means for cost information collection

(2) Construction Cost Control

No.	Construction Content
Control Items	
1	Cost Information Determination: Accurately determine the construction cost of each process based on construction progress
2	Cost Information Control: Enable construction units to intuitively understand the cost management status of the project at various stages
Scoring Items	
1	Establish an information-based design platform for plan collaboration on construction planning, funds, and materials, providing reference for subsequent construction schedule collaboration framework
2	Use 3D design technology to improve the accuracy of material, equipment, and construction quantity bidding, constraining design errors within reasonable limits
3	Adopt BIM 5D management mode to effectively control process, method, and construction cutting cost-related coefficients, visualizing management of contract funds and costs during construction, achieving material control
4	Automatic statistics of engineering quantities through input of actual building information in BIM models; generating cost information reports through the platform
5	Other intelligent equipment or information technology means for construction cost control

(3) Cost Comparison and Decision-making

No.	Construction Content
Control Items	
1	Data Comparison and Optimization: Intelligently compare and analyze actual collected data with model data, optimize fund usage, minimize project costs
Scoring Items	
1	5D Cost Management Mode: Effectively perform cost comparison and control during construction management, adopting more reasonable construction techniques to control costs
2	Cost Control Automatic Optimization System: Optimize fund usage, automatically optimize the project's planning, design, construction, operation, and maintenance costs to reduce construction costs
3	Other intelligent equipment or information technology means for cost comparison and decision-making

(4) Construction Schedule Information Collection

No.	Construction Content
Control Items	
1	Construction Schedule Information Control: Collect on-site progress for each period and work area, dynamically view overall project video monitoring in real time, and timely upload collected data to the management platform
Scoring Items	
1	Conduct drone aerial photography of overall construction progress, capturing visual progress of each period and work area, assisting project site layout and work area coordination
2	Use sensor devices instead of manual labor to effectively perceive construction data such as temperature and stress in complex and changing on-site environments
3	Use electronic maps and video tracking technology to establish real-time visual, seamless communication between remote locations and site, incorporating instant meetings for remote real-time monitoring of site work
4	Install time-lapse photography equipment on the construction site to record on-site construction conditions
5	In the smart construction site management platform: Project data is uploaded to the cloud management system in real time for data analysis; all project participants access relevant site information online in real time via the cloud, completing cloud applications like project schedule coordination and resource allocation, achieving multi-party collaborative work
6	Other intelligent equipment or information technology means for construction schedule information collection

(5) Construction Schedule Control

No.	Construction Content
Control Items	
1	Digital Construction Schedule Simulation: Conduct virtual simulation of construction processes after collecting actual work efficiency of various trades
2	Digital Warning of Deviations: Intelligently identify deviations between simulated schedule and actual progress, provide real-time warnings of schedule deviations and propose optimization solutions

No.	Construction Content
Scoring Items	
1	Review construction drawings based on BIM models, efficiently complete drawing reviews
2	Use BIM technology for spatial simulation of construction excavation, making technical briefings concise and intuitive
3	Fully simulate the real construction site scene in 3D dynamic form based on BIM models, obtaining realistic experience through VR
4	Use drones to collect control points and elevation information, match with BIM 3D models for similarity analysis, achieve automated aerial photography, modeling, 3D model similarity matching, providing comprehensive visual data expression for construction progress
5	Combine laser point cloud scanning technology and BIM technology to obtain geometric information of internal building space, generate point cloud models, input them into the digital information platform, compare with BIM models to generate dimensional deviation reports between physical structure and BIM model
6	Innovatively integrate BIM 4D technology with databases to construct a construction schedule information database for schedule optimization, virtual construction, actual progress acquisition, and recording of abnormal problems
7	Place the reporting content of each project phase in a centralized platform; automatically collect operational data for that phase to improve progress report generation efficiency; use BIM to connect different software to acquire and process project information in real time at various stages
8	Track rectification progress in real time via mobile APP one-click photos, voice, and short video auto-upload
9	Set time intervals for time-lapse photography, automatically record into short videos

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