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# Analyzing Critical Factors for the Smart Construction Site Development: A DEMATEL-ISM Based Approach

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**Abstract:** The wide and in-depth adoption of advanced information technologies within the construction industry has led to its revolution of all aspects; the construction site is not an exception. Recently, the notion of a smart construction site (SCS) has drawn the attention of all stakeholders within the industry. While the practice of SCS could be witnessed in various regions and the notion is mentioned frequently, the concept of SCS is still emerging, a sound framework for SCS development is still absent. As a bottom-up phenomenon, a systematic analysis of critical factors would provide all stakeholders with a comprehensive view of SCS development. In this research, previous research and existing practices of SCS are referred to, which helps to identify 17 critical factors for SCS development from the perspective of management, technology, and organization. The DEMATEL-ISM approach is introduced to conduct the factor analysis, and a questionnaire survey is conducted among 10 experts to investigate their attitudes on these factors. Following the proposed method, the 17 factors are classified into seven hierarchies and further categorized into three layers, i.e., effect layer, operational layer, and input layer, which helps to demonstrate the interrelationship among the critical factors for SCS development. The effect layer consists of the first to the third hierarchy, which contains the factors of cost (F2), safety (F4), schedule (F5), environment (F9), and quality (F3) management; these factors belong to the management perspective and reflect the expectations during SCS development. The operational layer consists of the fourth to the sixth hierarchy, which contains seven factors, namely, processing (F8), information (F10), communication and coordination (F15), personnel (F5), material (F6), equipment (F7), and management regulation (F17); these factors are critical in processing the input resources into the final effect of SCS development. The input layer only consists of the seventh hierarchy, which contains hardware and software facility (F11), integrated platform (F12), data sharing center (F13), smart decision system (F14), and technical team (F16); these factors represent the investment of SCS development. The systematic analysis of critical factors provides new insights on SCS development, which could be adopted as references for future SCS development by all stakeholders like government and construction enterprises.

**Keywords:** smart construction; smart construction site; DEMATEL; ISM; factor analysis

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## 1. Introduction

The traditional construction industry has long been blamed in various aspects, such as low efficiency, high accident rates, high energy consumption, and low technology. Recently, with the trends of new information and communication technologies (ICTs) adoption and requirements by diverse goals, e.g., Sustainable Development Goals (SDGs) [1], transformation and upgrading of the traditional construction industry has been a topical issue both in theory and industry [2]. The construction industry is typically a project-oriented industry [3]; construction sites are where the recourses are integrated under certain management measures to build the final products, like buildings or infrastructure. Therefore, construction sites receive high expectations in the transformation and upgrading processes of the traditional construction industry.

Recently, inspired by the smart planet and smart city [4], the concept of a smart construction site (SCS) has emerged in academic research, industrial practice, and government agendas [5]. The initiatives of SCS development tries to offer a novel framework and orientation for the transformation and upgrading of traditional construction sites by integrating advanced ICTs, such as BIM (building information modeling), cloud computing, big data, IoT (internet of things), and intelligent equipment within all fields like construction organizations management, construction management practices, etc. [6–9]. More precisely, SCS emphasizes the application of advanced ICTs within the lifecycle of construction projects by all stakeholders during construction site management practice [10]. Construction organization in SCSs could optimize their organizational structure and content in order to share critical data and break the information isolations. As a result, stakeholders could take effective management measures to achieve projects goals in SCSs, such as schedule, quality, safety, sustainability, etc.

However, as an emerging concept, SCS has not been well defined; meanwhile, a range of notions are frequently mentioned, such as digital construction site, which focuses on the digitization of construction projects [11], smart component, or objects, which emphasize enabling construction resources (e.g., machinery, device, and materials) [8,12] and intelligent construction, which employs sensors and automated machinery on construction sites to reduce manual operations [13], and similar notions like smart sites [14]. Simultaneously, the construction industry also makes great efforts in SCS practices. For example, the famous mega-project Hong Kong-Zhuhai-Macao Bridge employed the SCS model for construction site management, put forward the conceptual model for SCS, and also identified three key elements of SCS, namely information support platform, collaboration work, and intelligent construction management [15]. Other mega-projects, like railway engineering and petrochemical plant projects, also applied SCS to address information sharing or safety management [13,16]. Unfortunately, either the academic community or the construction industry reached a consensus on the definition and framework of SCS. In addition, the standard for SCS development is still missing at the government level. Instead of developing a sound framework for SCS or discussing a specific factor, a research gap exists that suggests a systematic analysis is in urgent demand to identify the critical factors for SCS development. At the same time, the roles of these critical factors in the path towards SCS should be well explored to help decision makers decide what and how efforts should be made.

To fill the research gap and achieve the objective of this research, we conducted a systematic review of the existing research and practice to identify the critical factors for SCS development instead of being entangled in discussing the concept of SCS innovatively. Meanwhile, the DEMATEL-ISM approach is introduced to demonstrate the roles and their interrelationship of these factors; therefore, a systematic review of previous studies is conducted in Section 2. Meanwhile, the practice of SCS development in China is also investigated, based on academic research and industrial practice, and an overview of critical factors affecting SCS development is outlined at the end of Section 2. Section 3 describes the research methods and framework applied in this study, and a conceptual model for SCS factor analysis is developed based on the DEMATEL-ISM approach. Section 4 presents the factor analysis processes and results. The research findings and implications are discussed in Section 5. Finally, the conclusions are marked in Section 6.

## 2. Literature Review

### 2.1. Application of Advanced Technologies in SCS

#### 2.1.1. Application of Single Advanced Technology

The adoption of technology is critical in SCS development. Recently, a large number of studies have focused on the integration of BIM technology and site construction management. Taking advantage of its characteristics of visualization, BIM is frequently used in displaying design schemes, detailed design, virtual construction, collision inspection, project management, and other technical applications [17,18]. For example, Zou discussed the potential of safety management enhancement through the integration of BIM [19]. Ding confirmed the role of BIM models to simulate the construction process so as to realize the real-time dynamic control of progress, cost, resources, and site, and proposes that 3D BIM could be extended to nD BIM by integrating more editable information [20]. However, in practice, the data of each stage is relatively isolated and lacks full integration with the management process. The value of BIM has not yet been fully developed, and some researchers turn to other technologies like IoT, big data, AI (artificial intelligence), and other emerging information technologies, which are mostly used for on-site video monitoring and equipment operation status monitoring [10]. For example, IoT has been introduced in the construction site to realize the ubiquitous link in the management of personnel, equipment, and environments, such as the real name management system of labor service, safety monitoring of lifting machinery, remote monitoring, and sensing of dust, noise, and other aspects of personnel, equipment, and environmental governance [21]. The application cost of big data in the analysis of the market price of construction material procurement and its influencing factors [22,23]. Mneymneh developed the algorithm of automatic monitoring sites by using computer vision [24]. Chen built a framework for application and technical models in construction site-based mobile computing [25]. Stumm et al. used tactile programming to realize robot-aided assembly construction [26].

Other researchers explored the effects of utilizing technology. From the qualitative aspect, through the comparative analysis of the time and cost data of traditional and smart construction sites, the digital construction method is considered to have greater economic benefits for complex structures [27]. Moreover, the application of smart construction technology would not only improve project management, but also bring about social benefits and brand accretion. From the quantitative aspect, Barlish et al. developed an input-output model to measure the benefits of BIM by comparing projects that do and do not use BIM [28]. Meanwhile, Barlish established an evaluation system to determine the value of BIM through investment-return analysis in a case study and showed that the application of BIM had significant positive benefits [28].

#### 2.1.2. Application of the Integration of Advanced Technologies

Smart construction sites have also witnessed the fusion of various smart technologies. In SCS development, many researchers focus on the integration of multiple technologies in smart construction sites [29]. Wu et al. systematically explored the application value of BIM and RFID technology in the whole life cycle of fabricated buildings [30,31]. Wei et al. combined BIM technology with cloud computing to automate the evaluation process in green building certification [28,32]. Wang formulated the methods of configuring BIM + AR prototypes, which demonstrates that extending to the site via the "hand" of AR, BIM solutions can address more real problems [33]. Irizarry et al. integrated BIM and GIS to track and control the status of on-site material supply and procurement [34]. In addition, some scholars also try to develop the integrated smart technology system to offer multi-functional and integrated applications and realize unified management through the integration of various modules. For example, Singh et al. [35] built the technical requirements and characteristic architecture of the BIM server for multi-disciplinary interaction. Hammad et al. designed a multi-agent system covering organization and coordination, field operation, information flow, and real-time simulation [36]. Teizer et al. explored the performance and applications of Long Range (LoRa) methods in construction and proposed an approach to integrating it with IoT to realize network tracking and monitoring for construction resource efficiency improvement [37].

Overall, the application and fusion of technologies are essential for the upgrading of a traditional construction site into a smart construction site. By referring to previous work, these technologies have merged into four categories; the first is software and hardware facilities like BIM, GIS, and smart machines. The second is integration platforms, the third is the data sharing center, and the last one is the intelligent decision center for decision makers.

### 2.2. Management in Smart Construction Sites

Despite advanced technologies playing critical roles in SCS development, as a project-oriented industry, a majority of resources, e.g., workers, materials, and machines, are gathered in construction sites to build the final products, which indicates that the construction sites are where the industry realizes its ultimate goals by fulfilling objectives as the construction project progresses within its lifecycle. The smart construction site is not an exception in achieving these objectives before delivering the final products. Therefore, the adoption of advanced technologies should energize the management measures to achieve these objectives.

Currently, project schedule, quality, safety, and cost management are hot topics in SCS management. Regarding schedule management, Park developed a prototype schedule management system by updating the 4D BIM and validated it using a Web and database-supported visualization method to realize the real-time information sharing of 4D-BIM, which illustrated enhanced communications and collaborations among schedule management [38]. In safety management, a variety of studies have focused on site safety monitoring [39] and early-warning systems [40]. For example, Yang proposed an RFID hazard identification system for construction site safety management and accident avoidance [41]. Guo built an early-warning system for unsafe worker behavior, integrating BIM and RFID [42], which includes safety training, identification of workers' access and path, identification of safety equipment wearing, identification of mechanical operation permission, and others. In material management, Han et al. established a BIM and point cloud model of material classification, generated with the construction material library (CML), so as to realize the efficient classification and selection of on-site materials [43]. In equipment management, Pradhananga collected and recorded equipment operation data with GPS and analyzed it on the software platform to realize the automatic evaluation of equipment operation status [44]. Elghaish [45] presented a methodology framework to develop a cash flow approach in the context of a BIM-based integrated project delivery method, which improved the accuracy of cash flow management during construction. In addition, construction site layout [46] and environmental problems [23,47] are also concerns of scholars.

Instead of separate management objectives, some scholars try to build a theoretical framework for multiple management objectives. Dakhli et al. present the ontology of information system architecture for SCS [6]. Succar established a three-axis framework model of BIM adoption in construction sites [48]. Jung discussed BIM adoption from various perspectives, such as project, organization, and industry-level, and then put forward a practical application framework [49]. In addition, Robin et al. built a novel path planning system based on real-time sensor inputs with cloud architecture and Belief-Desire-Intention (BDI) software agents and passed simulation and practical experiments, which have been effective in dealing with environmental disturbances [14]. Niu proposed a collaborative framework for emerging technologies in construction projects, which involves a three-hierarchy structure of physical perception application layer and cyber-application layer

### 2.3. Revolution of Construction Organization by SCS Development

Apart from technology and management, a number of studies focus on the revolution of construction by SCS development. The application of ICTs provides new opportunities for SCS coordination and communication improvement and helps achieve the synergy management of multiple elements in SCSs. Zhou et al. validated that SCS as a new framework for mega construction projects could realize collaborative work and information sharing among participants [50]. The research team from Sheffield University developed an information interaction platform integrating intelligent design monitoring to realize the coordination and communication of all stakeholders [51], which is critical for SCSs [52]. However, the adoption of advanced technologies also creates new challenges for construction site organization. For example, professional technical teams should be introduced to support construction and maintenance; meanwhile, supporting regulations should also be established to guide the development of SCSs.

### 2.4. Practice of Smart Construction Site

While the concept and framework of smart construction sites are still developing, the construction industry has already begun to actively forward SCSs in practice. Pilot projects of SCSs have been carried out in various regions of China. Therefore, it is beneficial to study the practice of SCSs to get a comprehensive idea about SCS development.

The concept of SCS comes from practice, and as a bottom-up concept, SCS has a long history. In 2014, personnel management system chip card swiping was introduced in the New World Center project in Shenyang to record the work information of every laborer, which joined the first tier of the SCS pilot project in China. In 2015, an SCS integrated management system based on the aforementioned system was developed in Wuhan. The system takes advantage of cameras to monitor the construction facilities and equipment on-site, and the videos are transited to the data center through mobile terminals. Recently, fingerprint, face recognition, and other technologies are also introduced to conduct personnel management, safety management, and other management objectives. In addition, cloud integration of multi-source data is developed in SCSs to support intelligent decisions. It can be seen that more and more smart construction sites are invested in urban construction; leading companies like Glodon™ have arisen in this domain to provide products and professional services for SCS development. In addition to the industry, the government also strives to promote SCSs in China. In 2020, the central government issued the 'Guidance on promoting the coordinated development of intelligent construction and building industrialization' [53], which is considered to be a powerful booster for SCS development. Since then, SCSs have entered a period of accelerated development.

### 2.5. Framework and Critical Factors for Smart Construction Site Development

By reviewing existing literature and practice, a brief framework of an SCS system could be obtained, in which SCSs are composed of management, technology, and organization systems, and each system consists of various critical factors. These factors are identified by referring to previous research or pilot projects of SCS, which affect the development of SCS, and the SCS framework is outlined in Figure 1. As shown in Figure 1, the management system of SCS contains 10 factors ranging from F1 to F10; these factors describe the critical management measures taken within the SCS. The technology system contains four factors, which represent the technological adoption in SCS development compared with a traditional construction site. The organization system emphasizes the organization revolution to cope with the development of SCS, e.g., the management regulations should be established to guide the development of SCS.

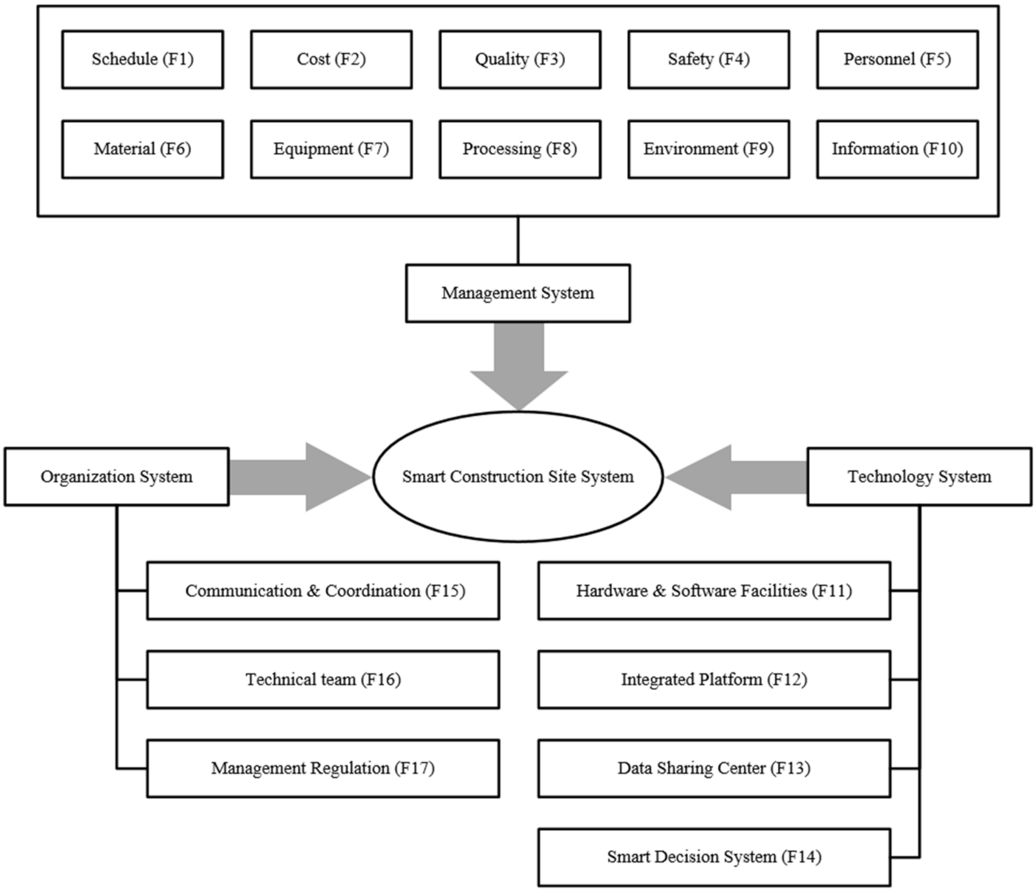


**Figure 1.** The framework of a smart construction site.

## 3. Research Methodology

### *3.1. Research Framework*

SCS is a complex system, and it is hard for the stakeholders to find their place in SCS development. Therefore, this research tries to systematically demonstrate the relationship among critical factors constituting SCSs and how these critical factors affect the development of SCSs. To achieve this goal, 17 critical factors are identified by reviewing previous research and practice of SCSs, as depicted in the last section, which lays the foundation for critical factor analysis. Then, the DEMATEL (decision-making trial and evaluation laboratory) ISM (interpretative structural modeling) integrated approach is developed in this research to conduct a factor analysis, which will be introduced in the following section. The DEMATEL-ISM approach helps to categorize the critical factors within diverse, interconnected hierarchies; the attribution of each hierarchy, as well as their relationship, would also be revealed. The results will help stakeholders within the development of SCS to get comprehensive knowledge and thereby take effective measures.

### *3.2. The DEMATEL-ISM Approach*

In this research, the decision-making trial and evaluation laboratory (DEMATEL) and interpretative structural modeling (ISM) are integrated as the DEMATEL-ISM approach to analyze the structure of the complex SCS system.

DEMATEL is an efficient and effective method for the identification and analysis of cause-effect chain components of a complex system like SCS. The DEMATEL method takes advantage of graph theory and matrix tools in systematic analysis by quantifying the logical relationship between the components of the complex system, and then the direct influence matrix could be obtained. Finally, the influence degree and affected degree of each component, as well as the cause degree and center degree, could be calculated, which helps to determine the relationship between components and their position in the complex system.

ISM is a method used to reveal the relational structure of a complex system. It constructs the adjacency matrix by judging the direct influence relationship between system components and obtains the reachability matrix by Boolean logic operation. Thus, the whole system is decomposed into hierarchical subsystems, and the hierarchical directed graph is used to reveal the structure of the complex system.

The identified 17 critical factors would be analyzed under the proposed framework using the DEMATEL-ISM approach, and the factor analysis procedures are demonstrated in Figure 2.

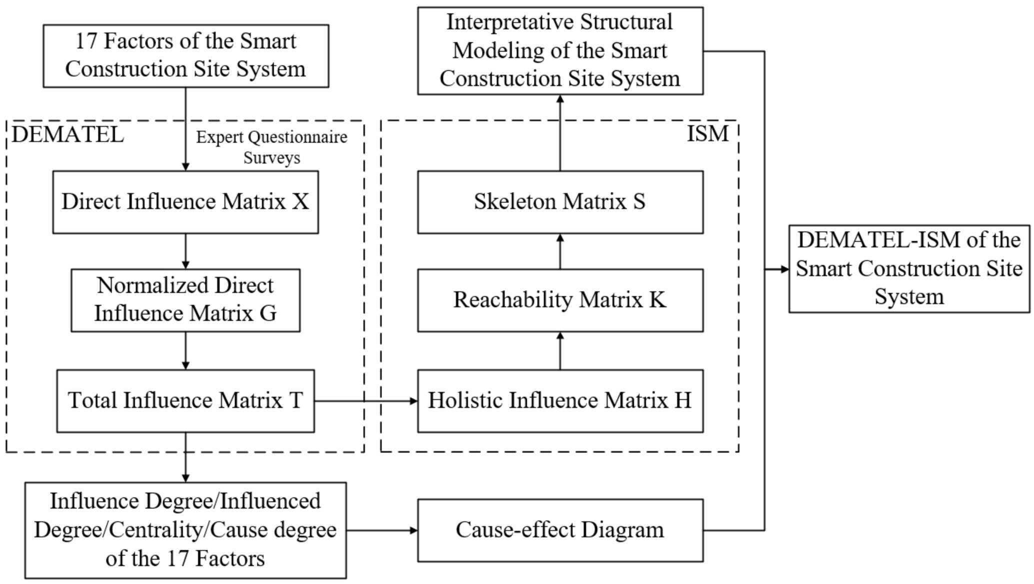


**Figure 2.** Research framework and factor analysis procedure.

## 4. Factor Analysis and Results

### *4.1. Factor Attribute Analysis Based on DEMATEL*

Step 1: Calculate the Direct Influence Matrix X

In order to reveal the relationship between the various factors within the smart construction site system, this paper conducted expert questionnaire surveys to invest their attitudes on these factors. The questionnaire survey was conducted among experts who are familiar with SCSs. Ten experts in the related field of engineering management, including four university professors and scholars, five high-ranking managers from construction enterprises who have rich experience in SCS development, one senior officer from the government who participated in establishing promotion policies of SCS development. Before the questionnaire survey, the information and background of this survey were introduced to ensure experts had good knowledge about this survey. Then, the experts were asked to make one-by-one judgments on the influence relationship between factors based on their own knowledge and experience. The rule is that if the influence relationship between $x_i$ and $x_j$ is judged as 'none', 'weak', 'medium', or 'strong', $x_{ij}$ would be defined as 0, 1, 2, or 3, respectively. Based on the results of the questionnaire survey, the average number method was used to determine each $x_{ij}$ to obtain the direct influence matrix X shown in Table 1.

**Table 1.** Direct Influence Matrix X.

| | F1 | F2 | F3 | F4 | F5 | F6 | F7 | F8 | F9 | F10 | F11 | F12 | F13 | F14 | F15 | F16 | F17 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| F1 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| F2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| F3 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| F4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| F5 | 2 | 1 | 1 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| F6 | 2 | 3 | 2 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| F7 | 1 | 1 | 2 | 2 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| F8 | 2 | 1 | 3 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| F9 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| F10 | 2 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 0 | 0 |
| F11 | 2 | 1 | 2 | 2 | 3 | 3 | 3 | 3 | 2 | 3 | 0 | 1 | 1 | 1 | 1 | 2 | 1 |
| F12 | 2 | 1 | 1 | 2 | 3 | 3 | 3 | 2 | 1 | 3 | 0 | 0 | 1 | 1 | 3 | 1 | 1 |
| F13 | 2 | 1 | 0 | 1 | 2 | 2 | 2 | 1 | 1 | 3 | 0 | 0 | 0 | 0 | 3 | 1 | 1 |
| F14 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| F15 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| F16 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 1 | 1 | 1 | 0 | 0 | 0 |
| F17 | 2 | 0 | 0 | 1 | 2 | 1 | 1 | 1 | 0 | 2 | 0 | 0 | 0 | 0 | 2 | 0 | 0 |

Step 2: Calculate the Normalized Direct Influence Matrix G and Total Influence Matrix T

The set of the sum of each row that directly affects the sum of each row in the matrix X is:

$$\sum x_{ij} = \{2,\ 0,\ 3,\ 0,\ 8,\ 10,\ 8,\ 7,\ 1,\ 8,\ 31,\ 28,\ 20,\ 23,\ 3,\ 6,\ 12\}$$

The maximum value is 31, and the normalized direct influence matrix $G$ is obtained by Formula (1):

$$G = \frac{1}{max \sum_{j=1}^{n} x_{ij}} X \tag{1}$$

Based on matrix $G$, the total influence matrix $T$ is calculated using MATLAB™ by Formula (2), in which $I$ represents the identity matrix. To make the layout of this manuscript more concise, the main context only presents the calculation formula and processes.

$$T = \lim_{n \to \infty} \left( G + G^2 + \cdots + G^n \right) = G(I - G)^{-1} \tag{2}$$

Step 3: Calculate Four Weights of Factors

According to the total influence matrix T, the influence degree, influenced degree, centrality, and cause-degree of each factor of the smart construction site system are marked as $f_i$, $e_i$, $m_i$, and $n_i$, $f_i$ indicates the degree that the factor could influence others, while $e_i$ indicates the degree to which this factor is affected by other factors. $m_i$ indicates the total influence of this factor in the system. As for $n_i$, whether it is positive or negative indicates that this factor is actively or passively affected in the system, which can be calculated with Formulas (3)–(6).

$$f_i = \sum_{j=1}^{n} t_{ij},\ i = 1,\ 2,\ \cdots,\ n \tag{3}$$

$$e_i = \sum_{j=1}^{n} t_{ji},\ i = 1,\ 2,\ \cdots,\ n \tag{4}$$

$$m_i = f_i + e_i,\ i = 1,\ 2,\ \cdots,\ n \tag{5}$$

$$n_i = f_i - e_i, i = 1, 2, \cdots, n \quad (6)$$

The results of DEMATEL are shown in Table 2; the results show that there are 6 cause factors and 11 result or effect factors in the 17 factors of the smart construction site system, among which the $m_i$ of the software and hardware technology facilities (F11) is the highest and echoes the fact that the application of technologies is critical for SCS development.

**Table 2.** Results of DEMATEL analysis.

| Factors | $f_i$ | $e_i$ | $m_i$ | $n_i$ | Ranks | Factor Attribution |
|---|---|---|---|---|---|---|
| F1 | 0.065 | 0.911 | 0.976 | −0.846 | 4 | effect |
| F2 | 0 | 0.664 | 0.664 | −0.664 | 12 | effect |
| F3 | 0.098 | 0.582 | 0.68 | −0.484 | 10 | effect |
| F4 | 0 | 0.666 | 0.666 | −0.666 | 11 | effect |
| F5 | 0.268 | 0.431 | 0.699 | −0.163 | 9 | effect |
| F6 | 0.34 | 0.394 | 0.734 | −0.054 | 7 | effect |
| F7 | 0.27 | 0.394 | 0.664 | −0.124 | 12 | effect |
| F8 | 0.24 | 0.324 | 0.564 | −0.084 | 15 | effect |
| F9 | 0.032 | 0.442 | 0.474 | −0.41 | 16 | effect |
| F10 | 0.275 | 0.516 | 0.791 | −0.241 | 6 | effect |
| F11 | 1.287 | 0.114 | 1.401 | 1.173 | 1 | cause |
| F12 | 1.13 | 0.072 | 1.202 | 1.058 | 2 | cause |
| F13 | 0.782 | 0.108 | 0.89 | 0.674 | 5 | cause |
| F14 | 0.88 | 0.108 | 0.988 | 0.772 | 3 | cause |
| F15 | 0.109 | 0.602 | 0.711 | −0.493 | 8 | effect |
| F16 | 0.409 | 0.177 | 0.586 | 0.232 | 14 | cause |
| F17 | 0.461 | 0.141 | 0.602 | 0.32 | 13 | cause |

Step 4: Draw the Cause-effect Diagram

With $m_i$ as the horizontal axis and $n_i$ as the vertical axis, the $m_i - n_i$ Cartesian coordinate system is drawn to represent the causality between the factors of the smart construction site system. In Figure 3, it can be seen that the $m_i$ of the schedule management (F1), software and hardware technical facilities (F11), integrated management platform (F12), data sharing center (F13), and smart decision-making system (F14) are relatively large (all exceeding 0.8), constituting the key factors of the smart construction site system. In addition, $n_i$ of F11, F12, F13, and F14 are greater, indicating that they have a strong influence on other factors of the smart construction site system.

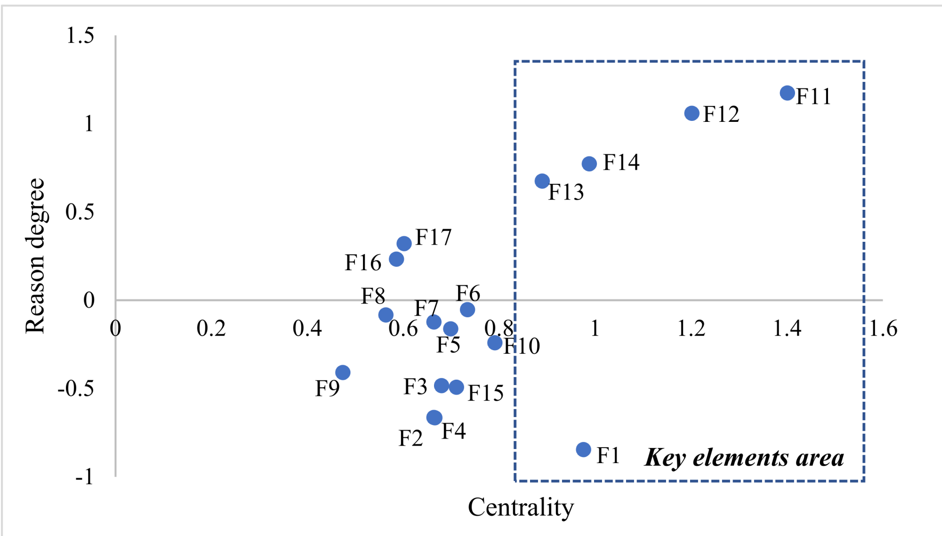


**Figure 3.** Cause-effect diagram of the factors of smart construction site system.

### *4.2. Hierarchy of Factors Using ISM*

After the DEMATEL analysis, the factors were further analyzed using ISM to uncover their hierarchy in the SCS system. The analysis procedure is as follows.

Step 1: Calculate the Holistic Influence Matrix H and Reachability Matrix K

The holistic influence matrix *H* is calculated by Formula (7), which reflects the overall influence relationship of the factors of the smart construction site system for the same reason.

$$H = T + I \tag{7}$$

Based on the holistic influence matrix *H*, the reachability matrix R is calculated according to the following rules: if $h_{ij} > \lambda$, let $k_{ij} = 1$, otherwise, $k_{ij} = 0$, where λ is the threshold. Through consulting expert opinions, this paper chose λ = 0.

Step 2: Hierarchy division based on matrix K

Based on the reachability matrix K, the reachable set and antecedent set of each factor can be obtained, denoted as R(i) and A(i). R(i) is the set of all columns corresponding to $k_{ij} = 1$, while A(i) is the set of all rows corresponding to $k_{ji} = 1$. Let the intersection of R(i) and A(i) be C(i). After using the result-first extraction method, which means that if C(i) = R(i), divide this factor into the first grade, then remove it, and repeat to get the factors of other grades, to determine the grade division; seven grades are eventually divided. The first grade includes elements F2 and F4, the second includes F1 and F9, the third grade includes F3, and so on. From this, the hierarchical relationship between the elements of the smart construction site system is obtained, as shown in Table 3.

**Table 3.** Hierarchy of factors within SCS.

| Factor | Reachable Set R(i) | Antecedent Set A(i) | C(i) | Hierarchy |
|---|---|---|---|---|
| F1 | 1,2 | 1,5,6,7,8,10,11,12,13,14,15,16,17 | 1 | II |
| F2 | 2 | 1,2,3,5,6,7,8,9,10,11,12,13,14,15,16,17 | 2 | I |
| F3 | 2,3,4,9 | 3,5,6,7,8,10,11,12,13,14,15,16,17 | 3 | III |
| F4 | 4 | 3,4,5,6,7,8,10,11,12,13,14,15,16,17 | 4 | I |
| F5 | 1,2,3,4,5,9,10,15 | 5,11,12,13,14,16,17 | 5 | V |
| F6 | 1,2,3,4,6,9,10,15 | 6,11,12,13,14,16,17 | 6 | V |
| F7 | 1,2,3,4,7,9,10,15 | 7,11,12,13,14,16,17 | 7 | V |
| F8 | 1,2,3,4,8,9 | 8,11,12,13,14,16,17 | 8 | IV |
| F9 | 2,9 | 3,5,6,7,8,9,10,11,12,13,14,16,17 | 9 | II |
| F10 | 1,2,3,4,9,10,15 | 5,6,7,10,11,12,13,14,15,16,17 | 10,15 | IV |
| F11 | 1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17 | 11,12,13,14,16 | 11,12,13,14,16 | VII |
| F12 | 1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17 | 11,12,13,14,16 | 11,12,13,14,16 | VII |
| F13 | 1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17 | 11,12,13,14,16 | 11,12,13,14,16 | VII |
| F14 | 1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17 | 11,12,13,14,16 | 11,12,13,14,16 | VII |
| F15 | 1,2,3,4,10,15 | 5,6,7,10,11,12,13,14,15,16,17 | 10,15 | IV |
| F16 | 1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17 | 11,12,13,14,16 | 11,12,13,14,16 | VII |
| F17 | 1,2,3,4,5,6,7,8,9,10,15,17 | 11,12,13,14,16,17 | 17 | VI |

### *4.3. DEMATEL-ISM Model of Factors in Smart Construction Site Development*

In order to establish a concise and explicit structure model, the repeated sides in the model are simplified. Then, according to the hierarchy division and reachability matrix K, and following the rule that if there is $s_{ij} = 1$ ($i \neq j$) in the previous grade, set $s_{kj} = 0$ at the following grade. Based on the skeleton matrix S, combined with the calculation results of DEMATEL, the DEMATEL-ISM structure chart of the smart construction site system is shown in Figure 4.

It can be seen that the factors F10 and F15 are strongly connected blocks, and all the factors (F11, F12, F13, F14, and F16) at the bottom are also strongly connected blocks. These two groups of blocks constitute two loops in the model, which reflects the influence relationship among the factors within the smart construction site system. The arrow line indicates that there is a direct influence relationship between the two connected elements.

On the other hand, the two factors that can be reached by the arrow line connections have an indirect influence relationship, and the dashed circle highlights the factors within it which influence each other.

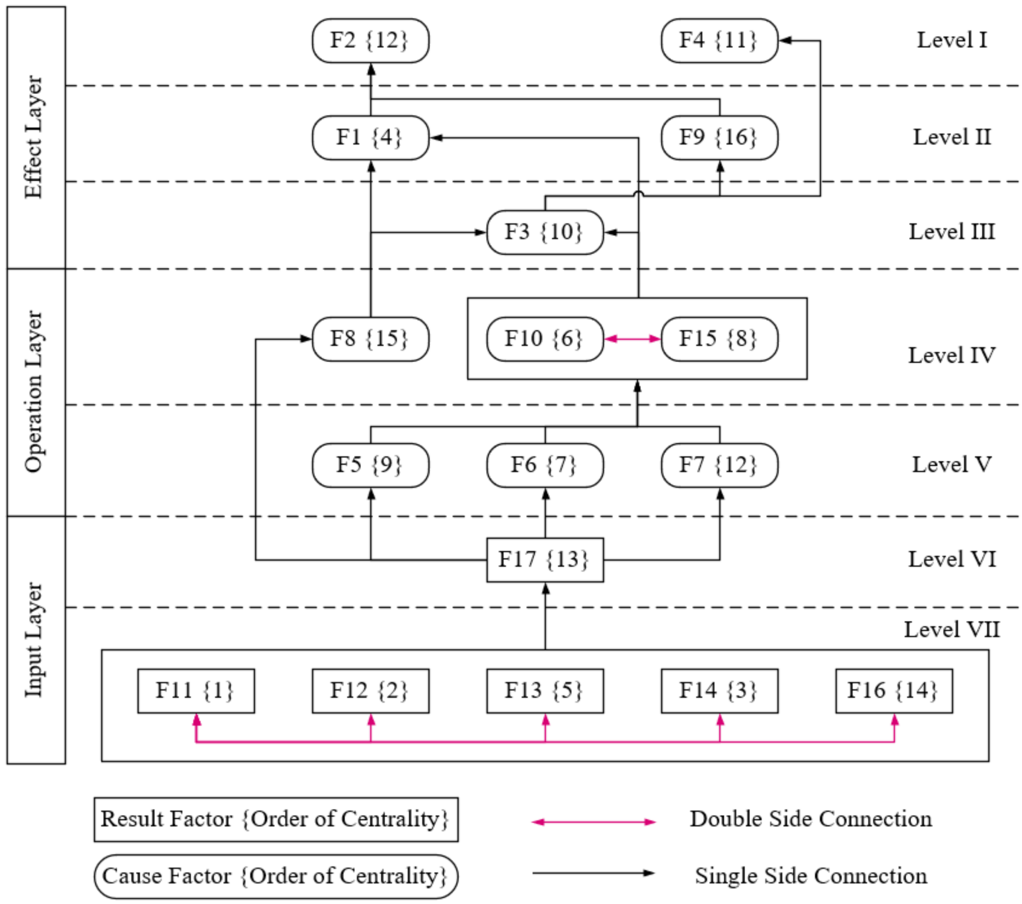


**Figure 4.** DEMATEL-ISM model of smart construction site system.

## 5. Research Findings and Implications

### *5.1. Research Findings*

According to the DEMATEL-ISM model, the various factors within the smart construction site system constitute a complex multi-layer hierarchical structure. First of all, cost management (F2) and safety management (F4) are the most direct factors of the entire smart construction site system, which reflects that the operational benefits, i.e., safety risk and cost reduction, are the most direct effects experienced by the stakeholders within the development of SCS develop [2,5,15]. Therefore, it is crucial to ensure the improvement of cost-effectiveness and safety benefits with technology investment in smart construction site development. In the second layer, schedule management (F1) and environmental management (F9) are secondary direct factors, both of which have impacts on F2. According to the order of centrality, F1 occupies a more important position in the smart construction site system. It can be seen that technology investments will have considerable impacts on improving production efficiency [8,15]. The third layer contains only one factor, namely quality management (F3), which directly affects factor F9 in the second hierarchy and F4 in the first hierarchy. The fourth hierarchy includes three factors, namely process management (F8), information management (F10), and communication and coordination (F15), located in the middle hierarchy of the whole model. Among them, F10 and F15 form a close mutual influence relationship, which demonstrates the close relationship between information and communication [18]. The fifth hierarchy includes personnel management (F5), material management (F6), and equipment management (F7), all of which belong to the basic production factors of the smart construction site and thereby have an indirect impact on the operation of the smart construction site system [14]. In addition, all factors within the first five hierarchies are result or effect factors; meanwhile, the factors of the last two hierarchies are cause factors. The sixth hierarchy contains only one factor, the management regulation (F17), which has profound impacts on the development of the smart construction site system [9,10]. Finally, software and hardware facilities (F11), integrated platform (F12), data sharing center (F13), intelligent decision system (F14), and technical team (F16) are the most fundamental factors in the structure, along with the development of SCS, these five factors have a close relationship and complex interactions among each other. Among them, four factors, namely F11, F12, F13, and F14, belong to the technical system; at the same time, their critical roles in SCS development could also be verified by their ranks of centrality [9].

By analyzing factors within each hierarchy, the DEMATEL-ISM approach could further help to categorize the seven hierarchies into three layers. The first layer contains the first to third hierarchies containing five factors from the management system, which could be named the effect layer. The effect layer indicates the higher expectations by all stakeholders by transforming traditional construction sites into smart construction sites. The second layer is the operation layer, which contains factors during the transformation processes; more specifically, these factors are the management measures that should be taken to achieve these effects of SCS, e.g., proper personnel management measures applied in SCS would enhance safety situations. The last one is the input hierarchy, which contains the investment of technologies like soft and hardware, platforms, and data sharing center, the establishment of supporting regulations, as well as intervention of technical teams.

### *5.2. Implications*

The DEMATEL-ISM approach uncovers the interrelationships of factors with the complex SCS system, which helps all stakeholders get a comprehensive idea about SCS and thereby take effective measures in developing SCS. According to factor analysis and the current status of SCS development, this research has the following implications for SCS development.

More investment could be given to accelerate the adoption of advanced technologies in SCS. According to the DEMATEL-ISM model, F11, F12, F13, and F14 are the key factors of a smart construction site system; more investment in these factors would increase the technological level of SCS, which echoes that currently the development of SCS wares the digital skin [9], therefore providing more advanced tools could enhance the management measures, and finally improve the performance of SCS.

Innovations in organization are as important as technical progress. Research findings show that compared with a traditional construction site, the involvement of technical teams is critical for supporting SCS success [18]. Meanwhile, management regulations issued within this field would not only orient the development of SCS, but also provide guidance for the practitioners [4].

Finally, a sound evaluation system for assessing SCS effects should be established. The development of SCS has been given high expectations by all stakeholders. According to the effect layers in the DEMATEL-ISM model, the development of SCS may generate various benefits to society for numerous aspects, such as safety, cost, schedule, quality, and environment. Therefore, a systematical evaluation system should be built, which would help the government to supervise the development of SCS [54]. At the same time, the construction enterprises could also take advantage of this evaluation system to improve their management measures or determine their investment.

## 6. Conclusions

The past few years have witnessed the fast development of SCS within the construction industry; great efforts have been made on SCS development from perspectives of management, technology, and organization by all stakeholders. However, the connotation of SCS has still been ambiguous, and either the academic or practice has reached a consensus on SCS concepts. Instead of interpreting the phenomenon, this research investigated the factors affecting the development of SCS. Seventeen critical factors within the development of SCS are identified by reviewing previous research as well as practices of the industry. The identified 17 factors outlined the framework of SCS from the perspectives of management, technology, and organizations. Results of the DEMATAL-ISM approach help to classify 17 factors into 7 hierarchies and demonstrate the interrelationship of these critical factors. The DEMATAL-ISM approach further categorizes these factors into three layers, i.e., effect layer, operational layer, and input layer. The identified three layers provide a more comprehensive view of the relationships of these critical factors.

This research has both theoretical and practical implications for stakeholders. From the theoretical perspective, the proposed research framework and research method offer a novel theoretical perspective for the further study of SCS within other countries with similar backgrounds. From the practical perspective, this research provides references for all stakeholders within the development of SCS; for example, the government officers could adopt these results to develop more detailed guidelines to promote SCS development to ensure the efficiency of the investment and quality of outcomes.

## 7. Limitations

The SCS development is still at the infancy stage, the connotation of SCS is still vague for all stakeholders. Therefore, this research, as an exploratory study on SCS, surely contains various limitations. For example, the relationship of the factors within the results is still qualitative; a further quantitative study could be conducted in the future. In addition, with the continuous development of information technology, more and more advanced methods will be applied to SCS in the future. Therefore, the contents involved in the SCS will be more complex, which needs to be persistently supplemented and improved in future works.

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