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Analyzing Critical Factors Influencing the Quality Management in Smart Construction Site: A DEMATEL-ISM-MICMAC Based Approach

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Abstract: The swift integration of advanced technologies in the construction sector has significantly propelled the adoption of smart construction sites (SCSs). Quality management (QM), a critical endeavor within the construction domain, is central to the operational success of construction projects. The establishment of quality management in smart construction sites (SCS-QM) specifically seeks to delineate the principal factors influencing quality management in the context of SCS, with the objective of enhancing overall project quality. This study has identified 19 pivotal factors impacting SCS-QM by drawing upon the 4M1E quality management framework and an extensive review of the literature. Utilizing the hybrid DEMATEL-ISM-MICMAC analytical framework, the research evaluates these factors in terms of significance, hierarchical structure, and interdependencies, thereby formulating targeted strategies for the advancement of SCS-QM. Through a systematic evaluation by nine experts, this study categorizes the influencing factors into nine levels, three layers, and four areas, further classifying them into four distinct impact typologies. The results underscore that those technologies, such as automation and intelligence, along with regulatory frameworks, comprehensive quality management standards, transparency of critical technologies, training of construction personnel, and effective process management, constitute the foundational elements crucial for enhancing SCS-QM.

Keywords: smart construction site; quality management; influencing factors; hybrid DEMATEL-ISM-MICMAC framework

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1. Introduction

The traditional construction industry has historically been the subject of critique due to its pronounced susceptibility to high accident rates, inefficiencies in production, excessive consumption of resources, and a paucity of technological integration [1,2]. This predicament has catalyzed urgent demands for substantial reform and modernization from both academia and industry stakeholders [3]. Concomitant with recent technological progress in information technology and escalating imperatives for sustainable development, there has been a significant surge in the industry's requisites for advanced informational and intelligent management systems [4]. Construction sites, the quintessential arenas for amalgamating diverse resources to fabricate buildings and urban infrastructure, are pivotal in driving industry-wide optimization. Therefore, enhancing these venues is imperative for the comprehensive transformation of the construction industry into a more efficient and technologically adept sector [5,6].

In recent years, the concept of smart construction sites (SCSs) has gained significant attention in academic, industrial, and governmental sectors. These sites utilize a variety of advanced information and intelligent technologies, including big data analytics, the Internet of Things (IoT), blockchain technology, and building information modeling (BIM). This technology suite forms a comprehensive platform designed to improve site management effectiveness, enable complex networked collaborations, support strong decision-making processes, and facilitate widespread knowledge sharing throughout the construction project life cycle [7,8]. The main goal of implementing such an intelligent site management system is to enhance the standard and efficiency of on-site operations by integrating cutting-edge information technology. This strategic integration aims to optimize the achievement of various project objectives, including quality, adherence to timelines, cost efficiency, occupational health and safety standards, and environmental sustainability throughout the project duration [9].

Quality management is deemed the quintessential "lifeline" of construction projects, playing an indispensable role in the management of construction sites [6,10]. The overarching aim of quality management is to ensure that construction projects adhere to specified quality benchmarks, thereby optimizing production processes via the minimization of defects and enhancement of operational efficiency [11]. Core interventions encompass quality evaluation, ongoing monitoring, identification of defects, formulation and execution of quality control strategies, and continuous training to elevate employee quality consciousness [12,13]. With the emergence of cutting-edge technologies and the extensive adoption of intelligent construction sites, it is imperative that the measures for quality management in construction projects be continuously and dynamically adjusted to satisfy evolving managerial demands, thus augmenting both the quality and operational standards of the projects.

As technological advancements proliferate and intelligent construction sites become ubiquitous, quality management frameworks must evolve to keep pace with new operational exigencies. At present, the bulk of scholarly discourse on construction project quality management remains anchored in traditional construction site paradigms. Research pertaining to quality management in smart construction sites (SCS-QM) often focuses narrowly on the development and application of singular technological solutions or on crafting intelligent on-site quality management systems [14]. These inquiries delve into the deployment of Internet of Things (IoT) technologies for on-site quality control [15], alongside leveraging big data and artificial intelligence (AI) for managing project quality and addressing defects [16]. The paucity of comprehensive theoretical frameworks for the quality management of smart construction sites impedes the development of a robust theoretical and practical base for SCS-QM. Therefore, it is critical to identify and dissect the pivotal factors influencing SCS-QM to deepen scholarly understanding and achieve practical advancements within the sector. Consequently, this research endeavors to explore SCS-QM by constructing an analytical framework of influencing factors, discerning specific factors, and delineating the interrelations and operational mechanisms among these factors, which are imperative for enhancing quality management at smart construction sites.

In pursuit of addressing these identified research deficiencies in SCS-QM, an extensive and systematic examination of existing literature was undertaken. Utilizing the 4M1E framework (Man, Machine, Material, Method, Environment) [17], pivotal factors impacting quality management at smart construction sites were pinpointed. Based on these insights, a questionnaire was devised to gauge the perceived importance of these factors among scholars and practitioners associated with smart construction sites. Following rigorous data collection and filtering, this study implemented the DEMATEL (Decision-Making Trial and Evaluation Laboratory), ISM (Interpretive Structural Modeling), and MICMAC (Matrix Impacts Cross-reference Multiplication Applied to a Classification) analytical techniques to establish a hybrid research framework [18]. This framework aims to elucidate the significance, hierarchical structure, and interdependencies of the key factors affecting quality management in smart construction sites, thereby proposing suitable quality management strategies aligned with the evolving demands of intelligent building environments.

2. Literature Review

2.1. Smart Construction Site

Smart construction sites utilize state-of-the-art technologies, including the Internet of Things (IoT) and big data, to sophisticate and improve management processes [19,20]. These technological applications contribute to enhanced productivity, strengthened safety measures, and elevated quality assurance while also optimizing the utilization of resources and reducing environmental detriments [21]. IoT technology allows for effective resource management through real-time surveillance of equipment, workforce, and materials. Additionally, the integration of big data and artificial intelligence (AI) equips construction sites with substantial data support and advanced predictive analytics. This technological synergy not only mitigates the complexities associated with site management but also amplifies the efficiency and security of construction projects [22,23].

The architecture of smart construction sites is organized into several layers: data acquisition, network transmission, data processing and storage, and application services. The data acquisition layer mainly focuses on the collection of diverse site-specific data via sensors and related technologies [24]. The network transmission layer ensures efficient data transfer to cloud services or data centers. The data processing and storage layer is where the data are analyzed and converted into actionable insights [22]. Subsequently, the application service layer uses these insights to facilitate decision-making related to project progression, quality assurance, and safety monitoring [23].

Recently, the utilization of intelligent construction site technologies has broadened to include aspects such as site management, safety and activity monitoring, real-time tracking, and identification of equipment activities. Sánchez et al. (2021) explored the BeSafe B2.0 intelligent multi-sensor platform, which notably diminishes the rate of accidents and occupational diseases by leveraging smartwatches and other sensors (e.g., in helmets or belts) to monitor workers' health statuses continuously at construction sites [25]. Jiang et al. (2021) delineated a cyber-physical system that aligns risk data across both simulated and actual construction environments, augmenting safety and risk management through enhanced data perception and analysis [14]. Jin et al. (2020) engineered an IoT-based surveillance system employing smart helmets and portable RFID triggers that actively monitor site personnel, offering efficient, user-friendly, and secure solutions for intrusion detection and localization [26]. Lee et al. (2023) devised an intelligent monitoring platform for construction safety by integrating artificial intelligence with Internet of Things technologies, which proactively ensures the safety of management staff and others by continuously observing site activities, effectively preventing access to hazardous zones and rapidly addressing emergency situations [27]. These studies collectively suggest that smart construction sites, fortified with cutting-edge technologies, not only heighten project efficiency and quality but also safeguard the health and safety of on-site workers.

2.2. Construction Quality Management

The International Organization for Standardization (ISO) defines quality as "the totality of features and characteristics of a product or service that bear on its ability to satisfy stated and implied needs [28]". Quality management in enterprises encompasses a series of managerial functions including planning, organizing, directing, coordinating, and controlling, aimed at enhancing product quality [29]. In construction, quality management is crucial for ensuring that projects meet predetermined quality standards across the design, construction, and maintenance phases [30]. The interplay of various factors influencing construction quality is traditionally modeled using the 4M1E quality management framework (Men, Machine, Material, Method, Environment). Zhang et al. (2023) employed the 4M1E framework to categorize and summarize quality factors in prefabricated construction, resulting in the development of a visualization-based Bayesian network quality factor evaluation model using ISM-BN. Existing research identified the construction phase and lack of worker responsibility as the most significant factors affecting building quality [17]. Mao et al. (2011), utilizing structural equation modeling, analyzed the impact of 4M1E factors on construction quality, discovering that human, environmental, and machine elements are crucial, with human factors also indirectly influencing construction quality through the effect on machine elements [31]. Zhou et al. (2020) integrated the 4M1E model with multi-source information fusion technology to identify and manage various risk factors in submarine tunnel construction comprehensively [32]. Pan et al. (2020) established a prefabricated construction safety evaluation model based on the 4M1E framework, utilizing the EW-SPA method to assess actual projects [33].

Recently, with the emergence of smart construction sites, an increasing number of studies have focused on quality management in these advanced settings. Zhang et al. (2023) explored the application of technologies such as BIM, IoT, virtual technologies, and artificial intelligence at smart construction sites to enhance construction quality management [34]. Hu et al. (2021) discussed how information technologies like IoT and AI can be leveraged to improve management capabilities in construction, detailing studies in personnel management, quality management, safety management, equipment management, and environmental management [35]. Jiang et al. (2021) proposed a quality management in smart construction site framework based on cyber-physical systems, which synchronizes virtual and physical construction site quality data through scenario reconstruction design, data sensing, data communication, and data processing modules, thereby enhancing construction quality [14]. Zhang et al. (2020) analyzed quality safety issues at construction sites and suggested that implementing training, education, and technological methods under the concept of smart construction sites could reduce quality safety issues and enhance site management efficiency [36]. Xie et al. discussed leveraging next-generation information technologies like digital twin technology to improve quality and safety management in the construction industry. Existing research indicated that advanced sensing and computing technologies can make the construction process computable and controllable, enabling digital management of construction sites, thereby enhancing building quality and safety and promoting the development of intelligent construction in China [37].

However, existing research predominantly focuses on the singular application of advanced technologies in quality management in smart construction sites, with limited studies establishing a comprehensive research framework for holistic assessment and analysis of factors affecting safety management in smart construction sites. In order to address this research gap, this study leverages the 4M1E quality management framework and conducts an extensive literature review to identify the factors influencing safety management in smart construction sites. Consequently, an influencing factor analysis framework for SCS-QM is constructed.

2.3. Influencing Factors of Quality Management in Smart Construction Site

2.3.1. Human

Human factors play a crucial role in quality management at smart construction sites, exerting a core influence on SCS-QM. Jiang et al. (2021) proposed that enhancing personnel training and raising safety awareness can significantly improve safety and quality management on construction sites [14]. Hu et al. (2021) highlighted that intelligent methods such as virtual simulation and data analysis in employee training can substantially enhance construction quality and safety management levels [35]. Shan et al. (2023) developed an intelligent identification system for detecting violations at construction sites using AI-based image recognition technology. This system monitors construction sites in real-time through cameras, detecting violations promptly and aiding management in taking immediate corrective actions to improve construction quality and safety [38]. Kim et al. (2022) tested the effectiveness of Smart Construction Safety Technology (SCST) in practical applications, finding that monitoring employees' health conditions with smart devices can significantly reduce accidents and enhance construction quality [39].

2.3.2. Machine

The continuous emergence of advanced technologies and the adoption of intelligent monitoring and maintenance of equipment have become critical factors influencing SCS-QM. Rossi et al. (2019) demonstrated that intelligent sensors, through real-time identification of equipment activity and energy consumption data, can detect equipment overload conditions and implement corrective measures, thereby enhancing construction quality and safety [40]. Luo et al. (2023) proposed an IoT and QR code-based smart construction site management platform, enabling real-time monitoring and remote control of construction site equipment such as tower cranes, thus reducing safety risks and improving construction quality [41]. Bian et al. (2017) designed an IoT-based intelligent management system for construction sites, capable of real-time monitoring of personnel, equipment, environment, and safety, thereby enhancing construction quality and safety management levels [42].

2.3.3. Material

As the primary input for construction projects, the intelligent management of materials plays a significant role in enhancing SCS-QM levels. Liu et al. (2021) emphasized the importance of real-time detection and management of materials in improving construction quality by utilizing BIM, IoT, virtual, and AI technologies at smart construction sites [43]. Lee et al. (2011) proposed a method for managing construction materials using smart mobile computing technology, improving the efficiency of material management on construction sites through real-time processing and inspection of material information [44]. Yi et al. (2023) suggested constructing a project material management system using IoT and BIM technologies to optimize material procurement and utilization processes through real-time monitoring of material usage and quality, thereby improving construction quality [45].

2.3.4. Method

Project management methods, regulations, and work standards have a significant impact on SCS-QM. Hu et al. (2021) explored the application of intelligent information management systems in construction, improving quality management capabilities from various aspects such as personnel management, quality management, safety management, equipment management, and environmental management [35]. Bucchiaron et al. (2019) introduced an IoT-based smart construction platform, enabling project managers to remotely manage multiple construction sites through real-time data analysis, thereby enhancing construction management efficiency and quality [46]. Kasim et al. (2021) developed an intelligent emergency detection framework integrating Industry 4.0 technologies, enhancing quality management at construction sites by including early emergency detection and potential hazard warnings, which helps improve construction quality [47]. Niu et al. (2019) developed an Occupational Health and Safety Management System based on Smart Construction Objects (SCO), leveraging AI technologies for automatic hazard identification and response, thus enhancing site safety and quality [48]. Zhong et al. (2012) proposed an ontology-based semantic modeling method that automates compliance checks for construction quality by modeling regulatory constraints such as OWL axioms and SWRL rules [49].

2.3.5. Environment

Environmental factors significantly impact construction quality. Utilizing intelligent environmental monitoring methods can effectively improve project construction quality. Milivojević et al. (2023) used IoT technology to monitor air quality parameters in real-time at construction sites, including concentrations of NO_2 and particulate matter (PM2.5 and PM10), along with meteorological parameters such as wind speed, wind direction, humidity, pressure, and temperature, ensuring the construction environment supports high-quality construction [50]. Cheung et al. (2018) combined wireless sensor networks and BIM technology to propose a real-time construction safety monitoring system for detecting and automatically removing harmful gases at construction sites, thereby ensuring construction quality and safety [51]. Jin et al. (2020) studied an IoT-based system for detecting, locating, and alarming unauthorized intrusions at construction sites, utilizing smart helmets and portable RFID triggers for real-time intrusion monitoring, which enhances site quality management [26].

2.4. Critical Influencing Factors of the SCS-QM

This study utilizes the Web of Science (WOS) core collection database and bibliometric analysis methods to identify the key influencing factors of SCS-QM. The advanced search strategy employed was: TS = ((“smart construction” OR “intelligent construction” OR “digital construction” OR “construction”) AND (“quality management”) AND (“factors” OR “influences”)) AND PY = (2018–2024). This strategy aimed to retrieve studies published between 2018 and 2024 that address various aspects affecting quality management in smart construction sites. The initial search yielded 234 journal articles. A second round of screening was conducted to refine the literature list and facilitate the identification of key influencing factors. The specific criteria for this screening included selecting high-level journal studies that made significant contributions to understanding SCS-QM influencing factors in the domains of Men, Machine, Material, Method, and Environment. Based on these criteria and after removing duplicates, 62 journal articles were ultimately selected. Through a comprehensive literature review and expert interviews, the influencing factors for SCS-QM identified in this study are presented in Table 1.

Table 1. Critical influencing factors of the SCS-QM.

Category	Factor NO.	Factors	References
Men	F1	Intelligent Training Systems	[14,52–55]
	F2	Worker Health Monitoring	[14,35,52,56,57]
	F3	Intelligent Worker Behavior Monitoring	[14,35,53,58]
	F4	Intelligent Performance Evaluation	[52,54,55,58]
Machine	F5	Intelligent Equipment Monitoring	[26,41,59–61]
	F6	Automation and Digitization	[62–64]
	F7	Intelligent Equipment Maintenance	[59,65–67]
Material	F8	Smart Material Tracking Systems	[14,41,68,69]
	F9	Material Quality Inspection	[43,70–73]
Method	F10	Intelligent Project Management Procedures	[14,26,35,58,59]
	F11	Intelligent Management of Construction Documents and Data	[35,36,38,58,74]
	F12	Emergency Management Systems	[71,73,75,76]
	F13	Key Technologies and Scheme Disclosure	[14,53,77,78]
	F14	Regulations and Policies	[14,30,35,53,71,79]
	F15	Quality Management Standards	[14,22,25,42,53,64,79]
	F16	Construction Project Acceptance Procedures	[4,36,45,53,61,73]
	F17	Quality Protection Monitoring in Construction Site Operations	[30,31,35,53,63]
Environment	F18	Intelligent Environmental Monitoring	[32,51,57,58,79]
	F19	Intelligent Disaster Early Warning	[23,28,35,52,53,79]

3. Methodology

3.1. Research Framework

The workflow for this study is shown in Figure 1. The research begins with a comprehensive literature review based on the 4M1E (Man, Machine, Material, Method, Environment) quality management framework. Following discussions with experts, 19 key factors were identified that influence quality management at smart construction sites. Data were collected by distributing questionnaires to nine experts. To systematically explore the complex interactions and hierarchy of factors influencing smart construction site quality management, we employed a sequential analytical approach integrating three advanced methodologies: DEMATEL, ISM, and MICMAC. Initially, the DEMATEL method was applied to identify and evaluate the direct and indirect relationships among the various factors, providing a detailed visualization of their interdependencies. This set the foundation for the subsequent ISM analysis, where we used the relationships delineated by DEMATEL to construct a structured model that organizes the factors into a clear hierarchy. Following this, the MICMAC analysis was utilized to further categorize the factors into four distinct groups—Autonomous, Dependent, Linkage, and Independent—based on their driving power and dependence. This methodological flow ensures a thorough understanding of the dynamics at play, enhancing the strategic decision-making process for quality management at smart construction sites.

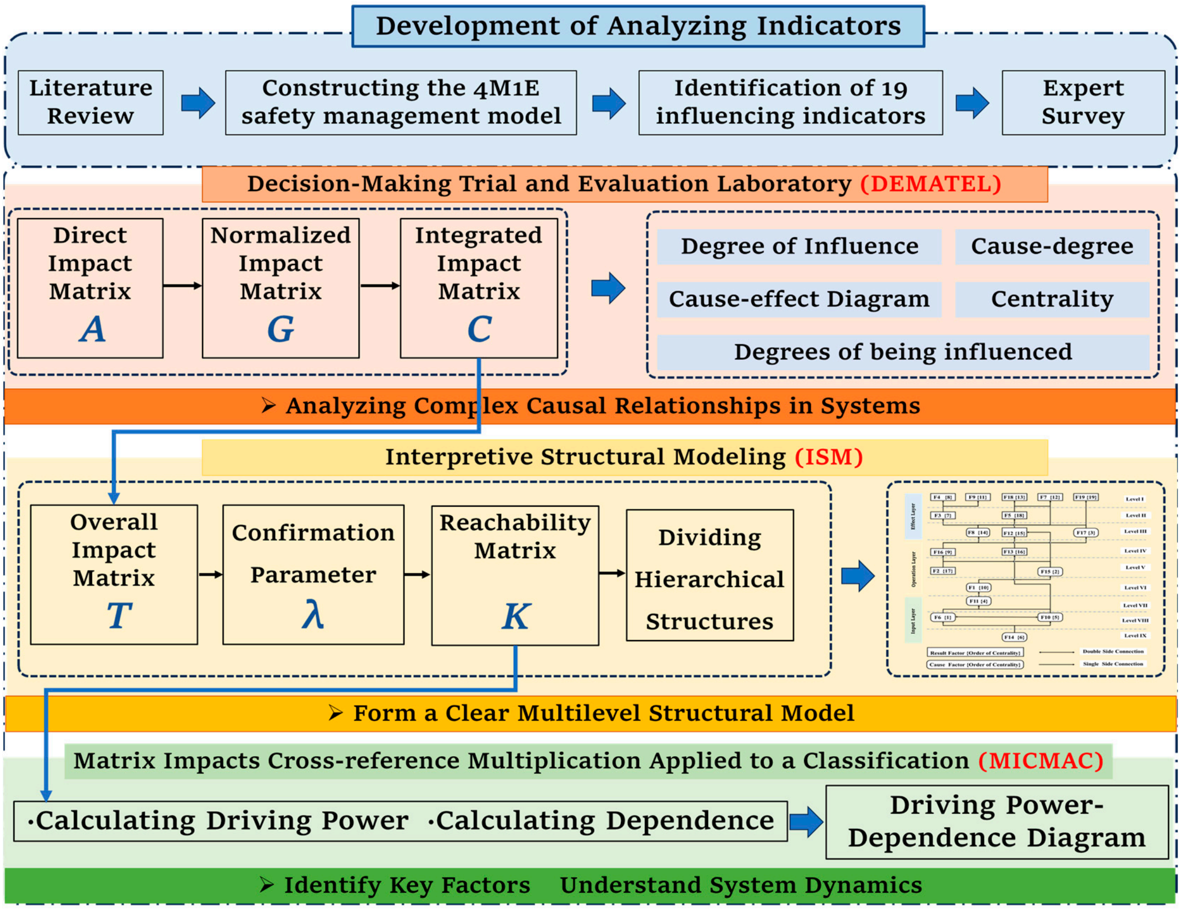

Figure 1. The workflow of the hybrid DEMATEL-ISM-MICMAC method.

3.2. Expert Survey

3.2.1. Expert Interviews

In this research, expert interviews were employed during two critical stages of the questionnaire development—the verification and optimization of index content and the data entry phase—to ensure the comprehensiveness, accuracy, and validity of the information recorded. Nine experts from the fields of smart construction site management and project quality management in China were invited to participate, with demographic details displayed in Table 2. These experts engaged in two rounds of discussions through offline workshops. In the first round of discussions, which focused on the verification and optimization of index content, the experts extensively debated the 19 influencing factors of the SCS-QM model, which had been identified through a systematic literature review. This discussion ensured that the identified factors were comprehensive, non-overlapping, and aligned with the research theme. In the subsequent round, focusing on data entry, the experts independently rated the relative importance of each index on the questionnaire scoring sheet, thereby ensuring the data's accuracy, objectivity, and independence.

Table 2. Survey population information.

Category	Sub-Category	Quantity (Unit: Persons)
Duration of Participation in Work or Academic Research	0–5 years	1
	5–10 years	5
	Over 10 years	3
Type of Employment	Owner	1
	Construction enterprise	4
	Design enterprise	1
	Government regulatory department	1
	Universities and other scientific institutions	2
Professional Rank	None	0
	Junior	2
	Intermediate	4
	Senior	3
Number of Smart Construction-Related Projects in Which They Were Involved	3–5	3
	5–10	4
	More than 10	2

3.2.2. Questionnaire Design

The questionnaire is structured into two modules: one collects basic information from respondents, such as work experience and employment details, and the other comprises a scoring table for the relative importance of 19 SCS-QM influencing factors. The first section aims to gather essential demographic and professional information from the participants. The second section, designed for expert evaluation, seeks to determine the relative importance of each influencing factor. In accordance with the data requirements of the DEMATEL method, this study employs a scoring range from 0 to 4 [18], where 0 indicates ‘no influence’, 1 ‘weak influence’, 2 ‘moderate influence’, 3 ‘strong influence’, and 4 ‘very strong influence’. This scoring system facilitates a comprehensive quantification and analysis of the respondents’ attitudes.

3.3. Data Analysis Methodology

3.3.1. DEMATEL Method

The Decision-Making Trial and Evaluation Laboratory (DEMATEL) methodology, devised by A. Gabus and E. Fontela during a 1971 conference in Geneva, applies principles of graph theory and matrix analysis to dissect intricacies within complex systems [80]. This technique encapsulates the interrelationships and immediate impacts among the components of a system in matrix form, enabling the quantitative assessment of the influence exerted by each element upon others reciprocally. Consequently, it facilitates the formation of cause-effect hierarchies and elucidates the systemic structure. By assimilating both direct and indirect influences, DEMATEL streamlines the intricate web of system interconnections. Additionally, it incorporates subjective data to inform the design and enhancement of the system [81]. The method proceeds through the following computational steps:

(1) Construct the direct impact matrix $\boldsymbol{A}$.

This study employs a 0–4 scoring method to construct the direct influence matrix $\boldsymbol{A}$, with the specific construction principles outlined in Table 3.

Table 3. The value of a_{ij} in directly impacts matrix $\boldsymbol{A}$.

Value	Descriptions
0	Factor *i* has no influence on factor *j*
1	Factor *i* has weak influence on factor *j*
2	Factor *i* has moderate influence on factor *j*
3	Factor *i* has strong influence on factor *j*
4	Factor *i* has very strong influence on factor *j*

Notes: When i = j, aij = 0.

(2) Calculate the normalized impact matrix ***G***.

Utilizing the normalization calculation method specified in Equation (1), the normalized matrix ***G*** was obtained.

$$\boldsymbol{G} = \frac{1}{max\sum_{j=1}^{19} x_{ij}}\boldsymbol{X} \tag{1}$$

(3) Calculate the integrated impact matrix ***C***.

The integrated impact matrix ***C*** represents the combined effect of direct and indirect influences among the factors, with the calculation method detailed in Equation (2). In order to maintain focus in the manuscript, the presentation of the normalized impact matrix ***G*** and the integrated impact matrix ***C*** has been omitted.

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

Herein, ***I*** denotes the identity matrix.

(4) Calculate four weights of factors.

Based on the integrated impact matrix ***C*** derived from the calculations mentioned above, the degrees of influence ($\boldsymbol{a_i}$), the degrees of being influenced ($\boldsymbol{b_i}$), the cause-degree ($\boldsymbol{N_i}$), and the centrality ($\boldsymbol{M_i}$) are computed. The specific formulas for these calculations are provided in Equations (3)–(6).

$$\boldsymbol{a_i} = \sum_{j=1}^{19} t_{ij}\,, (i = 1,\ 2,\ \ldots,\ 19) \tag{3}$$

$$\boldsymbol{b_i} = \sum_{i=1}^{19} t_{ji}\,, (j = 1,\ 2,\ \ldots,\ 19) \tag{4}$$

$$\boldsymbol{N_i} = \boldsymbol{a_i} - \boldsymbol{b_i}\ \ (i = 1,\ 2,\ \ldots 19) \tag{5}$$

$$\boldsymbol{M_i} = \boldsymbol{a_i} + \boldsymbol{b_i}\ (i = 1,\ 2,\ \ldots 19) \tag{6}$$

(5) Constructing the cause-effect diagram

This study uses $\boldsymbol{M_i}$ as the horizontal axis and $\boldsymbol{N_i}$ as the vertical axis to plot the cause-effect diagram with $\boldsymbol{M_i}$-$\boldsymbol{N_i}$ as the coordinate system.

3.3.2. ISM Method

The Interpretive Structural Modeling Method (ISM) is a widely employed approach in the field of system science, initially proposed by Professor Warfield in 1973 during his examination of complex economic structures [82]. This method involves organizing influencing factors of the system and, based on interconnections, constructing a directed graph. The application of Boolean logic enables the transformation of ambiguous hierarchical levels and complex system configurations into a clearly delineated ISM model. The advantage of this model is its capacity to integrate disparate viewpoints and experiences, thereby providing a lucid and intuitive representation of intricate relationships [83]. Consequently, it is frequently employed in the analysis of both macro- and micro-level issues. This paper presents a methodology for developing an ISM model based on the DEMATEL method, which streamlines the computational steps. The specific calculation method is as follows:

(1) Calculate the Overall Impact matrix ***T***

$$\boldsymbol{T} = \boldsymbol{C} + \boldsymbol{I} \tag{7}$$

Herein, ***I*** denotes the identity matrix.

(2) Confirmation Parameter $\boldsymbol{\lambda}$

In order to simplify the system structure, it is necessary to eliminate relationships with minor impacts by setting a threshold value $\boldsymbol{\lambda}$. In this study, the sum of the mean and standard deviation of the composite impact matrix $\boldsymbol{C}$ is used as the value of $\boldsymbol{\lambda}$, which provides a good fit for the research model [18]. The calculated value of $\boldsymbol{\lambda}$ is 0.0536.

(3) Construct the reachability matrix $\boldsymbol{K}$

The overall impact matrix $\boldsymbol{T}$ is transformed into the reachability matrix $\boldsymbol{K}$ using the method described in Equation (8).

$$\boldsymbol{K_{ij}} = \begin{cases} 0, & h_{ij} < \lambda \\ 1, & h_{ij} \geq \lambda \end{cases} \quad (i, j = 1,\ 2,\ \ldots,\ 19) \tag{8}$$

(4) Hierarchy division based on matrix $\boldsymbol{K}$

Interval and inter-level decomposition is a method used to reveal hierarchical structures within a system. Interval decomposition involves segregating elements of the system into separate subsystems, while inter-level decomposition further categorizes elements within the same system into different levels. Initially, it is necessary to identify the set of elements in the reachability matrix $\boldsymbol{K}$ for each factor $\boldsymbol{S_i}$, where elements in the row corresponding to $\boldsymbol{S_i}$ have $\boldsymbol{k_{ij}}$ = 1. This set is known as the reachability set $\boldsymbol{R(S_i)}$. Simultaneously, the set of elements where $\boldsymbol{k_{ij}}$ = 1 in the column corresponding to $\boldsymbol{S_i}$ is determined, known as the antecedent set $\boldsymbol{R'(S_i)}$. When the intersection of the reachability set $\boldsymbol{R(S_i)}$ and the antecedent set $\boldsymbol{R'(S_i)}$ contains only the factor $\boldsymbol{S_i}$ itself $\boldsymbol{(R(S_i) \cap R'(S_i) = S_i)}$, then factor $\boldsymbol{Si}$ is classified at the highest level. Subsequently, the rows and columns corresponding to factor $\boldsymbol{S_i}$ are removed from the reachability matrix $\boldsymbol{K}$, and the same method is applied to determine the levels of the remaining elements, ultimately dividing the elements into nine levels.

3.3.3. MICMAC Method

The Matrix Impacts Cross-reference Multiplication (MICMAC) method, incorporated into the Interpretive Structural Modeling (ISM) framework by Duperrin and Godet, significantly augments the evaluation of interconnections among system components [18]. This approach facilitates the classification of elements based on the dynamics of interactions, enabling a quantitative analysis of dependencies and driving forces. Specifically, MICMAC scrutinizes elements within the reachability matrix $\boldsymbol{K}$, interpreting a high driving power as indicative of a substantial influence exerted by an element, while a high dependence score reflects a greater vulnerability to external impacts. This nuanced methodology aids in pinpointing critical elements within the system, which are essential for comprehending its structural dynamics. The following outlines the specific computational steps utilized in this approach:

(1) Driving Power ($\boldsymbol{D_i}$)

$$\boldsymbol{D(i)} = \sum\nolimits_{\boldsymbol{j=1}}^{\boldsymbol{19}} \boldsymbol{k_{ij}} \tag{9}$$

(2) Dependence ($\boldsymbol{P_i}$)

$$\boldsymbol{P(i)} = \sum\nolimits_{\boldsymbol{j=1}}^{\boldsymbol{19}} \boldsymbol{k_{ji}} \tag{10}$$

Elements within the Matrix Impacts Cross-reference Multiplication (MICMAC) framework are categorized into four types: Autonomous (I), Independent (II), Linkage (III), and Dependent (IV). Autonomous elements in the first quadrant have low dependence and driving power, typically situated in the middle layer of the hierarchical structure, serving a bridging role. Independent elements in the second quadrant, characterized by strong driving power and low dependence, are positioned at the base of the structure, acting as foundational factors with enduring impacts on the system. Linkage elements in the third quadrant exhibit both high dependence and driving power, making them highly unstable as they are easily influenced and can significantly influence others. Dependent elements in the fourth quadrant, with high dependence but low driving power, are generally located in the upper layers with minimal impact on other elements. Each category uniquely contributes to the system's dynamics and structure, influencing its behavior and stability [84].

3.3.4. DEMATEL-ISM-MICMAC Analysis Framework

In recent years, the amalgamation termed DEMATEL-ISM has garnered prominence within the realms of management science and operations research. The integration of the Decision-Making Trial and Evaluation Laboratory (DEMATEL) and Interpretative Structural Modeling (ISM) methods enhances the methodological robustness and provides a multidimensional perspective on outcomes. Further augmenting this approach, numerous scholars have implemented the ISM-MICMAC methodology, wherein the MICMAC analysis is applied following the development of the ISM model. This process effectively leverages the capability matrix produced during the ISM phase for advanced numerical assessments. These evaluations systematically categorize factors by quantifying the driving forces and dependencies, thereby elucidating the underlying motivations of the studied variables and highlighting potential enhancements to the framework. This investigation utilizes the tripartite hybrid DEMATEL-ISM-MICMAC framework with the objective of executing an exhaustive analysis of the interrelations, hierarchical structures, and mechanisms that influence the pivotal factors governing SCS-QM [18].

4. Data Analysis and Results

4.1. Factor Attribute Analysis Based on DEMATEL

A questionnaire scoring table was constructed based on 19 critical influencing factors of the SCS-QM outlined in Table 1. Experts were engaged to assess these interactions using a predefined scoring protocol detailed in Table 3. The scoring data collected from nine experts were averaged and adjusted to the nearest whole number to form the direct impact matrix ***A***, shown in Table 4. For each individual question, the maximum difference in scores among the experts was no more than 1, demonstrating strong consistency and reliability in the findings.

Table 4. Direct impact matrix ***A***.

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17	F18	F19
F1	0	0	3	2	0	0	1	0	2	0	0	0	0	0	3	2	2	1	0
F2	1	0	1	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0
F3	0	0	0	4	0	0	1	0	3	1	0	0	0	0	0	0	0	1	0
F4	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F5	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	2	0
F6	3	0	3	3	0	0	1	1	3	3	4	0	3	0	4	4	4	1	0
F7	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F8	1	0	2	1	0	0	2	0	0	0	1	0	0	0	1	1	0	0	0
F9	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1
F10	2	0	1	2	0	2	1	0	2	0	4	0	2	0	2	2	3	1	0
F11	3	1	4	4	0	0	1	2	4	0	0	0	0	0	4	4	2	1	0
F12	0	0	0	0	2	1	1	0	1	0	0	0	1	1	0	0	0	1	0
F13	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0
F14	1	0	2	1	0	4	1	0	1	4	2	4	4	0	2	2	0	1	0
F15	0	0	4	4	0	2	1	1	3	2	0	2	1	2	0	3	3	1	0
F16	0	0	1	0	0	0	0	2	0	0	0	0	0	0	1	0	2	0	0
F17	1	1	2	4	0	0	4	1	4	0	1	1	1	0	2	1	0	4	2
F18	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F19	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0

Subsequent DEMATEL analysis results, displayed in Table 5, reveal that among the 19 influencing factors of the SCS-QM, there are 8 causal factors and 11 effect factors. Notably, the factor automation and robotics (F6) demonstrates the highest centrality, highlighting its pivotal role in driving the progress of SCS-QM. To further clarify the causal connections among these influencing factors within the SCS-QM framework, this research has developed a cause-effect diagram illustrated in Figure 2.

Table 5. Results of DEMATEL analysis.

Factors	a_i	b_i	M_i	N_i	Rank	Attribute
F1	0.633	0.443	1.076	0.189	10	Causal
F2	0.208	0.282	0.490	−0.075	17	Effect
F3	0.317	0.911	1.229	−0.594	7	Effect
F4	0.063	1.056	1.119	−0.993	8	Effect
F5	0.112	0.128	0.240	−0.016	18	Effect
F6	1.179	0.759	1.938	0.420	1	Causal
F7	0.033	0.710	0.743	−0.678	12	Effect
F8	0.351	0.303	0.654	0.048	14	Causal
F9	0.117	0.958	1.075	−0.841	11	Effect
F10	1.074	0.377	1.451	0.698	5	Causal
F11	1.152	0.433	1.585	0.719	4	Causal
F12	0.307	0.339	0.646	−0.033	15	Effect
F13	0.071	0.433	0.503	−0.362	16	Effect
F14	1.294	0.131	1.425	1.162	6	Causal
F15	1.583	0.328	1.911	1.255	2	Causal
F16	0.274	0.804	1.078	−0.530	9	Effect
F17	0.975	0.651	1.626	0.324	3	Causal
F18	0.033	0.640	0.673	−0.607	13	Effect
F19	0.056	0.142	0.198	−0.086	19	Effect

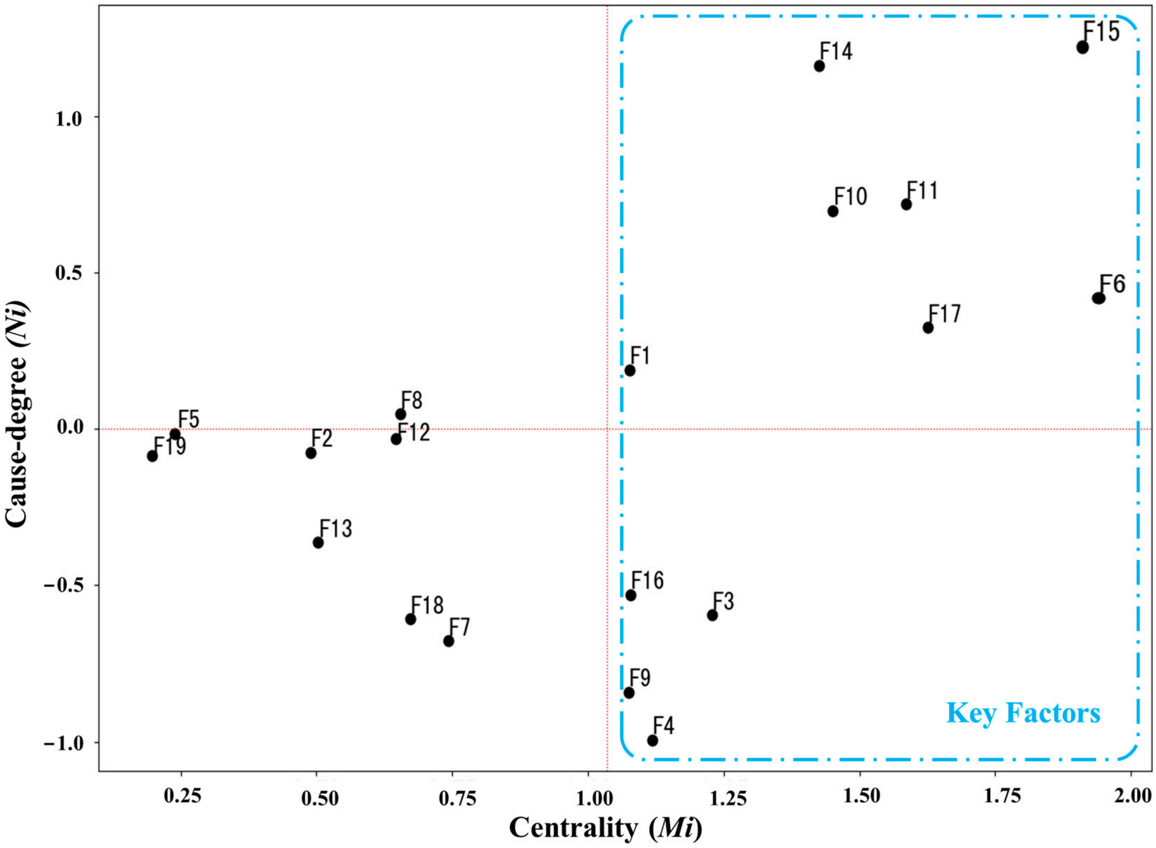

Figure 2. Cause-effect diagram of critical factors influencing the SCS-QM.

Causal Relationship and Importance Analysis

(1) Analysis of Degrees of Influence and Being Influenced: The factors ranking in the top three for degrees of influence ($\boldsymbol{a_i}$) are automation and digitization (F6), regulations and policies (F14), and quality management standards (F15). This indicates that these factors have a significant impact on others. The top three factors for degrees of being influenced ($\boldsymbol{b_i}$) are intelligent performance evaluation (F4), material quality inspection (F9), and intelligent project management procedures (F10), suggesting that these factors are highly susceptible to influence from others.

(2) Analysis of Cause-degree ($\boldsymbol{N_i}$) and Centrality ($\boldsymbol{M_i}$): In Figure 2, causal factors are positioned above the axis, indicating that these factors have a significant impact on others. Effect factors are located below the axis, suggesting that these factors are more susceptible to the influence of causal factors. A higher centrality indicates a greater level of importance. The top three factors in terms of influence include automation and digitization (F6), quality management standards (F15), and key technologies and scheme disclosure (F17).

4.2. Hierarchy of Factors Using ISM

Following the DEMATEL analysis, the Interpretive Structural Modeling (ISM) methodology is employed to delve deeper into the hierarchy of factors within the SCS-QM system. The reachability matrix $\boldsymbol{K}$, essential for this analysis, is detailed in Table 6. This matrix enables the establishment of hierarchical relationships among the elements of the SCS-QM system, which are clearly outlined in Table 7. From the ISM analysis and the insights derived from Table 7, the 19 influencing factors are systematically organized into nine distinct levels, creating a multi-level hierarchical structure model illustrated in Figure 3. Furthermore, based on the hierarchical positioning, these factors are segmented into three primary groups: the Input Layer, the Operation Layer, and the Effect Layer [85]. This structured categorization not only clarifies the roles of each factor but also enhances the understanding of the interdependencies and the overall dynamic within the SCS-QM framework.

Table 6. Reachability Matrix $\boldsymbol{K}$.

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17	F18	F19
F1	1	0	1	1	0	0	0	0	1	0	0	0	0	0	1	1	1	0	0
F2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
F3	0	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
F4	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F5	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	1	0
F6	1	0	1	1	0	1	1	0	1	1	1	0	1	0	1	1	1	1	0
F7	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
F8	0	0	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0
F9	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
F10	1	0	1	1	0	1	1	0	1	1	1	0	1	0	1	1	1	1	0
F11	1	0	1	1	0	0	1	1	1	0	1	0	0	0	1	1	1	0	0
F12	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0
F13	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0
F14	0	0	1	1	0	1	1	0	1	1	1	1	1	1	1	1	0	0	0
F15	0	0	1	1	0	0	1	0	1	1	0	1	0	0	1	1	1	1	0
F16	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1	0	0
F17	0	0	1	1	0	0	1	0	1	0	0	0	0	0	0	0	1	1	1
F18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
F19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

Table 7. Hierarchy of factors within SCS-QM.

Factors	Reachability Set $R(S_i)$	Antecedent Set $R'(S_i)$	Intersection	Hierarchy
F1	1, 3, 4, 9, 15, 16, 17	1, 6, 10, 11	1	VI
F2	2, 16	2	2	VI
F3	3, 4, 9	1, 3, 6, 8, 10, 11, 14, 15, 17	3	II
F4	4	1, 3, 4, 6, 10, 11, 14, 15, 17	4	I
F5	5, 7, 18	5, 12	5	II
F6	1, 3, 4, 6, 7, 9, 10, 11, 13, 15, 16, 17, 18	6, 10, 14, 15	6, 10, 15	VIII
F7	7	5, 6, 7, 8, 10, 11, 14, 15, 17	7	I
F8	3, 7, 8	8, 11, 16	8	III
F9	9	1, 3, 6, 9, 10, 11, 14, 15, 17	9	I
F10	1, 3, 4, 6, 7, 9, 10, 11, 13, 15, 16, 17, 18	6, 10, 14, 15	6, 10, 15	VIII
F11	1, 3, 4, 7, 8, 9, 11, 15, 16, 17	6, 10, 11, 14	11	VII
F12	5, 12	12, 13, 14, 15	12	III
F13	12, 13	6, 10, 13, 14	13	IV
F14	3, 4, 6, 7, 9, 10, 11, 12, 13, 14, 15, 16	14, 15	14, 15	IX
F15	3, 4, 7, 9, 10, 12, 15, 16, 17, 18	1, 10, 11, 15, 17	10, 15, 17	V
F16	8, 16, 17	1, 2, 6, 10, 11, 14, 15, 16	16	IV
F17	3, 4, 7, 9, 17, 18, 19	1, 6, 10, 11, 16, 17	17	III
F18	18	5, 6, 10, 15, 17, 18	18	I
F19	19	17, 19	19	I

Note: The number in the Hierarchy column indicates the level in Figure 3.

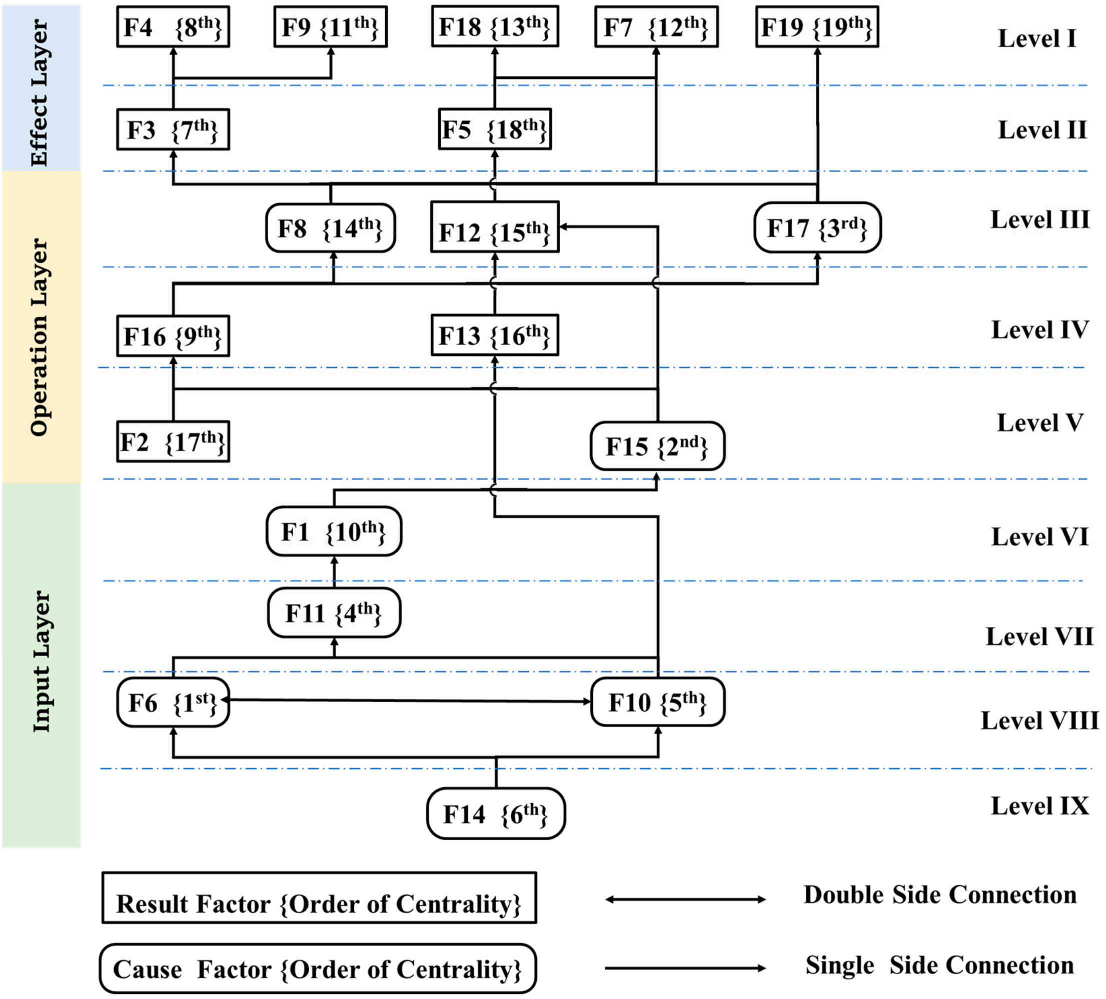

Figure 3. Hierarchical structure of critical factors influencing SCS-QM.

Hierarchical Structure Analysis

(1) Input Layer (Levels VII to IX): This layer forms the foundation of the SCS-QM system, incorporating fundamental factors with long-term influences on the system's upper elements. Crucial factors in this layer include regulations and policies (F14), automation and digitization (F6), intelligent project management procedures (F10), and intelligent management of construction documents and data (F11).

(2) Operation Layer (Levels IV to VI): Positioned in the middle, this layer contains factors that bridge the foundational input factors with the uppermost effect-oriented elements. It includes intelligent training systems (F1), worker health monitoring (F2), quality management standards (F15), construction project acceptance procedures (F16), and quality protection monitoring in construction site operations (F13).

(3) Effect Layer (Levels I to III): This topmost layer includes surface-level direct factors that immediately impact the SCS-QM. It encompasses a wide array of functions, such as intelligent performance evaluation (F4), material quality inspection (F9), intelligent environmental monitoring (F18), intelligent equipment maintenance (F7), intelligent disaster early warning (F19), intelligent worker behavior monitoring (F3), intelligent equipment monitoring (F5), smart material tracking systems (F8), emergency management systems (F12), and key technologies and scheme disclosure (F17).

4.3. Results of Driver–Dependency Relationship of Critical Factors Influencing the Development of SCS-QM

Based on Formulas (9) and (10), driving power and dependence are calculated and plotted in a Driving Power-Dependence Diagram, as shown in Figure 4.

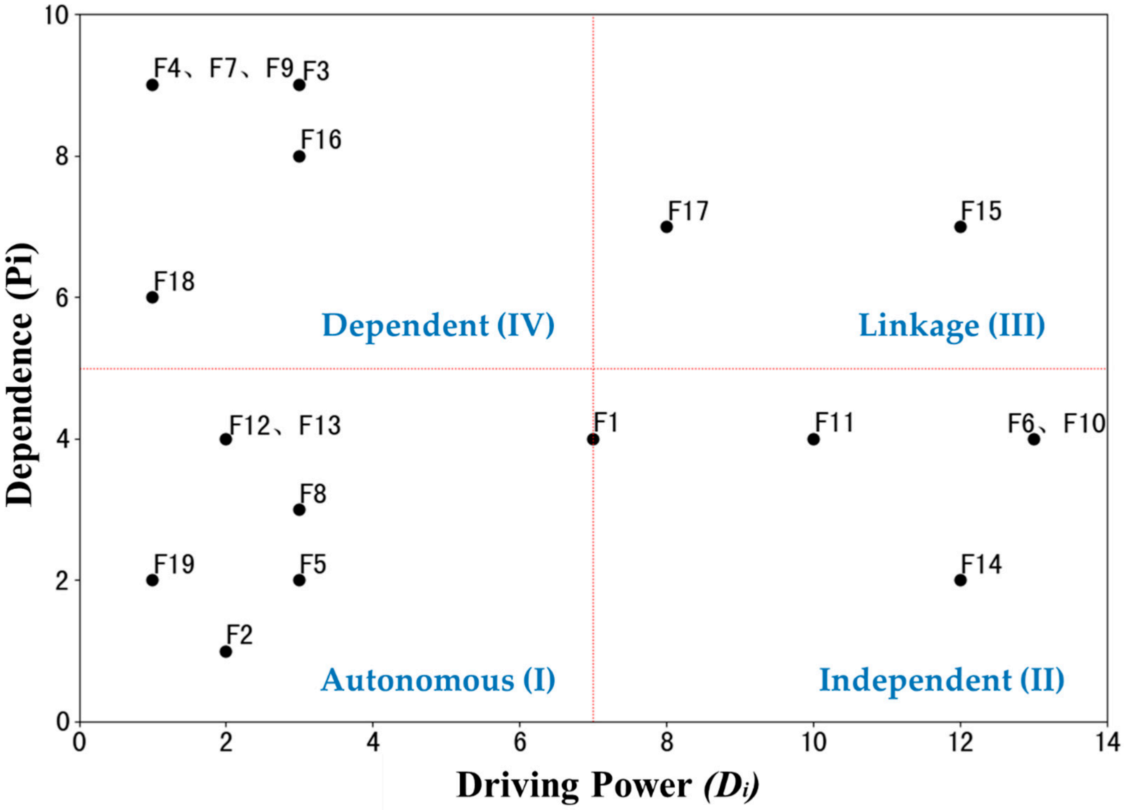

Figure 4. MICMAC analysis of critical factors influencing the SCS-QM.

Driver–Dependency Relationship Analysis

(1) Autonomous Factors (Quadrant I): These factors are characterized by low dependency and driving power, implying that the influence on the system is generally indirect or weaker. Included in this quadrant are worker health monitoring (F2), intelligent

equipment monitoring (F5), intelligent disaster early warning (F19), smart material tracking systems (F8), emergency management systems (F12), and quality protection monitoring in construction site operations (F13).

(2) Independent Factors (Quadrant II): Situated in this quadrant are factors that exhibit strong driving power but low dependency, making them pivotal to the system's functioning. This group includes intelligent training systems (F1), intelligent management of construction documents and data (F11), automation and digitization (F6), intelligent project management procedures (F10), and regulations and policies (F14). These elements are crucial, often exerting substantial direct influence across the system.

(3) Linkage Factors (Quadrant III): Factors in this quadrant have both high driving power and high dependency, which makes them highly dynamic and critical for transmitting influences and integrating feedback within the system. This group consists of quality management standards (F15) and key technologies and scheme disclosure (F17).

(4) Dependent Factors (Quadrant IV): These factors have strong dependency but weak driving power, typically positioned at the upper echelons of the ISM model and influenced predominantly by other elements. The ability of these elements to directly influence other parts of the system is limited, making the impact largely indirect. Included here are intelligent worker behavior monitoring (F3), intelligent performance evaluation (F4), intelligent equipment maintenance (F7), material quality inspection (F9), construction project acceptance procedures (F16), and intelligent environmental monitoring (F18).

4.4. Comprehensive Analysis of SCS-QM Influencing Factors Based on the Hybrid Research Framework

Based on the comprehensive hybrid DEMATEL-ISM-MICMAC research framework constructed in this study, the 19 key influencing factors of SCS-QM have been meticulously categorized into nine levels, three layers (Input Layer, Operation Layer, Effect Layer), and four types (Autonomous factors, Independent factors, Linkage factors, and Dependent factors). The analysis results of the hybrid research framework are detailed as follows:

(1) Input Layer: This layer incorporates five factors (F14, F6, F10, F11, F1), all situated within the independent quadrant, underscoring their role as fundamental drivers of SCS-QM development. Enhancements in these factors can indirectly and directly catalyze the advancement of SCS-QM by influencing the dynamics of upper-layer factors. Additionally, MICMAC analysis highlights that factors F6, F11, F10, F14, and F1 possess high centrality, thereby exerting significant impacts on SCS-QM.

(2) Operation Layer: Encompassing seven factors (F8, F12, F17, F16, F13, F2, F15), this layer presents a diverse interaction of roles. Factors F2, F8, F12, and F13, situated in the Autonomous quadrant, display low centrality, indicating minimal mutual interactions and impacts within the SCS-QM system. Conversely, factors F15 and F17, located in the Linkage quadrant, show high centrality and play a pivotal role in transmitting influences across the system, thereby heavily impacting SCS-QM. Factor F16, positioned in the Dependent quadrant, also demonstrates high centrality, underscoring its significant influence on SCS-QM despite its high susceptibility to other influences.

(3) Effect Layer: This layer consists of seven factors (F4, F9, F18, F7, F19, F3, F5). Factors F3, F4, and F9, located in the Dependent quadrant, exhibit high centrality, having a direct and profound influence on SCS-QM. Meanwhile, factors F7 and F18, also in the Dependent quadrant, and factors F5 and F19, in the Autonomous quadrant, show lower centrality, indicating a comparatively reduced impact on the SCS-QM system.

In order to offer a clear visual representation of the hybrid framework analysis, this study encapsulates the results in Table 8, featuring a systematic categorization of influencing factors according to respective roles and impacts within the SCS-QM system. This structured approach facilitates a deeper understanding of how each factor contributes to the dynamics and efficacy of SCS-QM.

Table 8. Summary of Analysis Results Based on the hybrid Framework.

Layer	Driving Power-Dependence	Centrality	Factors	Impact on SCS-QM
Input Layer	Independent	High	F1, F6, F10, F11, F14	Direct High
Operation Layer	Autonomous	Low	F2, F8, F12, F13	Weak
	Linkage	High	F15, F17	Direct High
	Dependent	High	F16	Indirect High
Effect Layer	Dependent	High	F3, F4, F9	Indirect High
		Low	F7, F18	Weak
	Autonomous	Low	F5, F19	Weak

5. Discussions

Quality management has emerged as a pivotal aspect in the evolution of smart construction sites. Employing the DEMATEL-ISM-MICMAC hybrid framework, this study conducted an analysis of 19 key factors affecting SCS-QM. This section will elaborate on the findings from Section 4. Additionally, the nine experts participating in this study engaged in thorough and in-depth discussions regarding the research results, ensuring consistency between expert opinions and data analysis.

5.1. Discussion of Analysis Results

(1) The research delineates that automation and digitization (F6) wield the most significant influence within the SCS-QM framework. These elements are pivotal in deploying intelligent quality control mechanisms within smart construction environments. Enhancements in automation and digitization equip smart construction sites with advanced management technologies and elevated operational efficiencies, thereby catalyzing the progression of SCS-QM [14,86]. Simultaneously, regulations and policies (F14) serve as a cornerstone within the ISM system, shaping the entire SCS-QM landscape. These specific regulations and policies directly influence management procedures, set monitoring standards, and promote the integration of innovative technologies. Additionally, intelligent training systems (F1), intelligent project management procedures (F10), and intelligent management of construction documents and data (F11) exert considerable effects on the SCS-QM system [85]. Intelligent training systems augment safety awareness among workers and clarify operational protocols at smart construction sites, directly impacting the quality of projects [54]. The robust drivers of intelligent project management processes, in conjunction with automation and digitization, affect other elements and the overall SCS-QM system. Effective and scientifically-driven project management processes amalgamate various monitoring methods to establish appropriate operational norms, significantly enhancing the quality management efficacy and standards at smart construction sites. Intelligent management of construction documents and data establishes the digital infrastructure of the entire SCS-QM system, offering strong data support and facilitating the intelligent management and analysis of complex data from monitoring systems, thereby guiding quality management decisions at smart construction sites [71,87].

(2) Quality management standards (F15) are identified as the second most influential factor within the SCS-QM system. The development of these standards profoundly impacts SCS-QM, laying both the policy and operational foundation for quality management. This factor is also notably influenced by other determinants, such as regulations related to smart construction, the degree of automation and digitization in projects, and the overall project management workflows [88,89]. Enhancements to F15 should simultaneously address these aspects. Key technologies and scheme disclosure (F17), ranking third in terms of direct impact on the SCS-QM system, is also prone to external influences. Disclosing essential technologies and construction processes identifies critical risks and challenges during construction phases, enabling the implementation of strategies to enhance project quality significantly, which in

turn impacts SCS-QM. This factor must also consider legal regulations and quality management standards during its optimization [59].

(3) Intelligent worker behavior monitoring (F3), intelligent performance evaluation (F4), material quality inspection (F9), and construction project acceptance procedures (F16) exert an indirect yet substantial influence on the SCS-QM system. Located within the ISM's effect layer, factors F3, F4, and F9 are influenced by foundational elements, thereby indirectly impacting SCS-QM. Within project quality management, monitoring human aspects holds central importance; thus, intelligent oversight of worker behavior and performance evaluations are crucial for ensuring compliance with operational standards. These factors are affected by various elements such as worker training, health conditions, and project management processes. Enhancements to these indirect factors should prioritize foundational elements, such as improving the quality of worker training and conducting health inspections to ensure personnel adhere to precise construction standards and requirements. The quality monitoring of construction materials also significantly influences project quality, although the quality of on-site materials largely depends on traceability and control over the production and transportation processes of materials, making this an indirect influence on project quality [59]. The outcomes of construction project acceptance procedures considerably affect SCS-QM, with acceptance results directly determining the compliance with quality standards of completed project segments. However, the management of project quality relies more on proactive prevention and in-process control, making post-completion acceptance an indirect yet vital factor [37].

5.2. Strategies for Enhancing SCS-QM

This study synthesizes six principal research insights (I1, I2, I3, I4, I5, I6), proposing corresponding strategies (S1, S2, S3, S4, S5, S6) aimed at fostering the high-quality advancement of SCS-QM.

I1: Automation and digitization are identified as exerting the most substantial impact on SCS-QM.

I2: Comprehensive legal frameworks and policies are acknowledged as foundational to SCS-QM.

I3: An extensive and methodologically sound quality management process is deemed essential for SCS-QM.

I4: The disclosure of pivotal technologies and construction processes is recognized as a crucial technological safeguard for the realization of SCS-QM.

I5: The intelligent monitoring of construction personnel's performance is highlighted as playing a central role in SCS-QM.

I6: Emphasis on process control for construction quality, such as material quality traceability, is crucial. Retrospective control measures like material quality inspection and construction project acceptance procedures serve as assurance measures for implementing SCS-QM, indirectly influencing SCS-QM.

Proposed Strategic Enhancements Based on Research Insights

S1: Integrate sophisticated automation and digital solutions, such as building information modeling (BIM), Internet of Things (IoT), and artificial intelligence (AI), to facilitate three-dimensional visualization and intelligent quality management [45]. Employ real-time data acquisition devices to elevate the precision and timeliness of information, thus augmenting decision-making efficiency and monitoring capacity in quality management.

S2: Formulate and refine legislative regulations and normative standards pertinent to quality management at smart construction sites [14]. Specify the requirements for intelligent quality management and auxiliary equipment, delineate key aspects of intelligent quality control, and unify quality control protocols [90].

S3: Execute a comprehensive quality management scheme under the smart site paradigm, including intelligent quality inspections and audits at pivotal project phases.

Utilize a specialized data analytics platform to process data sourced from intelligent monitoring devices [87]. Apply machine learning algorithms to forecast potential quality issues, ensuring adherence to quality standards and advancing the sophistication of intelligent quality management and decision-making processes [52].

S4: Initiate detailed technical disclosures prior to project commencement, elucidating the application scope and specific responsibilities associated with smart technologies [59]. Deploy drones for aerial site surveillance and progress tracking and implement smart sensors to monitor environmental and safety conditions at construction sites. For critical construction techniques and processes, employ three-dimensional technological applications like BIM for visualization simulations to ensure construction quality [23].

S5: Implement advanced monitoring systems, such as wearable devices and AI video analytics, to monitor safety behaviors and operational quality of workers in real time, promptly identifying and rectifying non-standard operations [87]. Additionally, leverage augmented reality (AR) and virtual reality (VR) for conducting intelligent training sessions, thereby enhancing the training quality of construction personnel [54].

S6: Establish an exhaustive material quality traceability system, ensuring all materials are reliable and compliant with standards [73]. Conduct stringent on-site material inspections and acceptance protocols, manage materials through RFID and barcode technology, ensuring each batch of materials is accompanied by comprehensive quality records and source information [69]. Further, emphasize the development and application of intelligent material quality monitoring (e.g., non-contact measurements) and sophisticated construction acceptance processes (e.g., 3D point cloud scanning modeling) as post-construction quality assurances.

6. Conclusions

Conducted within the framework of the 4M1E quality management system and supported by a thorough systematic literature review, this study identified 19 critical factors affecting SCS-QM. The research employed the hybrid DEMATEL-ISM-MICMAC framework. Initially, the DEMATEL approach delineated effect and causal factors, performing a centrality analysis on the 19 factors to assess impact within the SCS-QM system. Subsequently, the ISM method classified factors into nine levels and three layers (Input Layer, Operation Layer, and Effect Layer), clarifying the hierarchical structure within the SCS-QM system. The MICMAC method further categorized these factors into four types (Autonomous, Independent, Linkage, and Dependent), explicating the interdependencies and driving forces among them. Based on the hybrid framework, this study identified four categories of factors that significantly influence SCS-QM (as listed in Table 8) and proposed corresponding strategic interventions to promote the high-quality development of SCS-QM. The findings underscore that the implementation of advanced technologies such as automation and digitization, robust legal and regulatory frameworks, comprehensive quality management systems, transparency in key technologies, enhanced training for construction personnel, and strengthened process controls for material quality traceability significantly affect SCS-QM.

The implications of this study are significant for both theoretical and practical stakeholders involved in SCS-QM. Theoretically, the incorporation of the hybrid framework into SCS-QM research introduces a novel theoretical and methodological perspective for exploring quality management at smart construction sites. Practically, this study provides industry practitioners with theoretically substantiated strategies for enhancement, thus facilitating ongoing advancements in the quality management of smart construction sites.

7. Limitations

Contemporary scholarly inquiry into quality management at intelligent construction sites remains embryonic. Hence, this investigation, serving as a preliminary exploration into SCS-QM, inherently presents certain limitations. Notably, the selection of nineteen influencing factors identified within this study might not be entirely comprehensive. Furthermore, the determination of the critical parameter λ within the ISM methodology could benefit from the integration of expert panels, which would enhance the validity and applicability of the constructed hierarchical relationships. Additionally, with ongoing advancements in regional technologies, the conceptual scope of smart construction sites is expected to broaden, suggesting that the research frameworks and methodologies employed will require continuous refinement in subsequent studies.

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