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WHAT HINDERS INTERNET OF THINGS (IOT) ADOPTION IN THE CHINESE CONSTRUCTION INDUSTRY: A MIXED-METHOD

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Abstract. Although the Internet of Things (IoT) has aroused much interest as a potential approach for improving various construction activities, the extent of its adoption remains limited. The multiple barriers that prevent the wider adoption of IoT in the construction industry need detailed investigation. However, limited research has attempted to understand the barriers to IoT adoption. Therefore, this study aims to identify the critical barriers to IoT adoption in the construction industry and explore the prioritization and hierarchical structure of the barriers factors. Data were collected from relevant literature and feedback from Chinese industry experts, sixteen barriers against IoT adoption were identified and categorized based on the TOE framework assessed in the construction industry. An integrated interpretation structure model and decision-making and trial evaluation laboratory (ISM-DEMATEL) approach is adopted to analyze the interdependence between identified constructs and their intensities. In addition, the identified constructs are also clustered into a suitable group using MICMAC analysis. Results show that inadequate infrastructure, lack of governance, and top management support are the fundamental barrier against IoT adoption. By revealing the mutual relationships and interlinking of barriers, this study will help researchers and practitioners in the construction industry to focus on strategic efforts to overcome these obstacles to effective IoT implementation. This research revealed the barriers to IoT implementation in the Chinese construction industry. Also, it provides methodological tool references for exploring the impact factor of other similar innovative technology applied in this industry.

Keywords: Internet of Things (IoT), construction industry, adoption, barriers, DEMATEL, ISM, MICMAC.

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1. Introduction

The construction industry is generally considered to be fragmented, inefficient, and low in productivity (Ozorhon & Cinar, 2015; Wang et al., 2021). Some challenges, such as payment delays, unknown responsibility, time delays, and security incidents, are common in this industry (Abbasi et al., 2020; Alinaitwe et al., 2013). Many of these problems can be traced to poor communication, lack of traceability, and information delays (Agdas & Ellis, 2010; Zhong et al., 2017). As digital technology becomes more ubiquitous, the construction industry is also undergoing profound changes (Alizadehsalehi et al., 2020; Noruwa et al., 2020; Thramboulidis & Christoulakis, 2016). Internet of Things (IoT) may be a promising approach to solving these problems. IoT has considerable potential in the construction industry because it can capture project data in real-time and achieve visibility and traceability (Luo et al., 2020; Oke et al., 2022a). For example, achieve real-time monitoring (Cheryl et al., 2021; Costin & Eastman, 2019), increase the speed of information processing (Wu et al., 2022; Yang et al., 2020), simplify the construction process (Wang et al., 2020; Wu et al., 2022), and enable better construction process control and optimization (Li et al., 2018).

Despite the positive advantages offered by IoT, the adoption of IoT in the construction industry is at a very early stage (Nara et al., 2021; Tang et al., 2019). Adopting new technologies is not always smooth and accessible (Niu et al., 2019). The adoption process has described a series of activities: knowledge, persuasion, decision-making, implementation, and validation (Rogers, 1995). At any node, influences from technology, organization, and environment may interfere with or even block the adoption of new technologies (Parente & Prescott, 1994). In the construction industry, the adoption and implementation of IoT is a complex process and many obstacles require immediate attention, such as security issues (Chen et al., 2014; Khan & Salah, 2018; Pal et al., 2021), high costs (Gamil et al., 2020; Oke et al., 2022b; Tang et al., 2019), inadequate infrastructure (Oke et al., 2022b), and lack of top management support (Ghosh et al., 2020). However, few studies have provided a comprehensive understanding of the factors that hinder IoT adoption; while ongoing research indicates that identifying these factors play a significant role in predicting the successful diffusion of this technology (Demirkesen & Tezel, 2021). Above all, these barriers are highly interrelated and can potentially affect and be affected by a multitude of other barriers (Alaloul et al., 2020; Raj et al., 2020). By identifying the uppermost, deep, and surface barriers for IoT adoption, such a categorization can aid government and construction firms in rationally allocating resources to overcome obstacles and develop aggressive strategies for high-priority barriers. However, the relationships among the key barriers themselves have been overlooked in previous studies, where they considered the barriers as isolated factors, independent of their context and environment (Gamil et al., 2020; Oke et al., 2022b). Overall, the existing research lacks a comprehensive framework to clarify the inner logic of IoT adoption barriers, which can reduce complexity and avoid the consequences of failure. Therefore, this study aims to explore the interrelationships between barriers to implementing IoT in the Chinese construction industry. Specifically: (1) to identify critical barriers to adopting IoT in the Chinese construction industry; (2) to assess the causality and dependence among these factors; (3) to assess the hierarchical structure between these factors.

To achieve these objectives, a literature review was conducted and expert feedback was collected to develop an integrated barrier factor system. After that, an integrated interpretation structure model and decision-making and trial evaluation laboratory (ISM-DEMATEL) approach were adopted for modelling analysis of key influences. A multilevel hierarchical structure of the influential factors is constructed using the ISM method. The importance of each impediment, its causal relationship, and the strength of the influence between them are examined by applying DEMATEL.

2. Literature review

A literature review was conducted in three aspects to gain a broader understanding of related research's current status and investigate the barriers to IoT adoption. One was to analyze the current state of research on IoT in the construction industry to identify research gaps. The second is to analyze the research on the MCDM method in the construction industry and, finally, to identify the barriers to IoT adoption in the construction industry through the literature review.

2.1. IoT in the construction industry

IoT may be defined as the interconnection of sensing and actuating devices that provide the ability to share information between platforms through a unified framework and develops a common operation screen for innovative applications (K. K. Patel & S. M. Patel, 2016). It is globally regarded as one of the most important emerging technologies widely used in various fields (I. Lee & K. Lee, 2015; Liu et al., 2019). Therefore, researchers have conducted extensive exploration work, from the concept, characteristics, and framework, to the adoption, application, challenges, and future research opportunities of IoT (Jia et al., 2019). Moreover, scholars have discussed the challenges of adopting IoT in various industries, such as supply chain management, healthcare, finance, banking and insurance, and manufacturing; these of focused on the technical, organizational, and environmental aspects.

Although IoT offers a unique match with the construction industry (Alaloul et al., 2020; Lam et al., 2017), the research associated with IoT in the construction industry is relatively minor and focuses mainly on two aspects. On the one hand, the studies discussed the use of IoT in the construction industry using theoretical or qualitative methods. For example, Jia et al. (2019) summarized the general technologies of IoT used in the construction industry and introduced several recent applications of IoT in buildings to achieve the key goals of smart buildings. Ghosh et al. (2020) summarized the key driving forces for IoT adoption by reviewing the literature related to IoT in construction. Niu et al. (2019) reviewed the conceptual development, strengths, and weaknesses of IoT in the construction industry through a literature review system. On the other hand, they study the application and potential advantages of IoT in the construction industry. For example, Dave et al. (2016) pointed out that IoT can comprehensively solve the information flow requirements that span the life cycle of construction projects. Zhou and Ding (2017), Chen et al. (2020), and Liu et al. (2020) studied the monitoring automation of the construction industry and pointed out that IoT can provide a complete, real-time, and reliable automation system for construction process monitoring. Zhong et al. (2017) and Zhou et al. (2021) suggested that integrating IoT and BIM can achieve real-time visibility and traceability in prefabricated buildings. Wang et al. (2019) pointed out that IoT can effectively reduce financial risks by visualizing pledges and the number, location, and status. Although it has been widely studied concerning the construction industry, the research of IoT is still in their infancy considering the huge potential and challenges of IoT.

2.2. Application of MCDM methods in the construction industry

MCDM is a method used to evaluate and compare different options based on multiple criteria or factors (Biswas et al., 2023; Rani et al., 2021). Various MCDM methods, including single and hybrid approaches, have been used by many researchers in the domain of the construction industry (Jato-Espino et al., 2014). Tan et al. (2021) examined 45 articles combining MCDM with BIM and found that the five major application domains are sustainability, retrofit, supplier selection, safety, and constructability. Maghsoodi and Khalilzadeh (2018) identified and evaluated the construction projects' critical success factors by employing the Fuzzy-TOPSIS approach. Hussain et al. (2023) established a green, lean and six sigma implementation model for the sustainable construction industry to analyze the driving forces through the ISM-MICMAC approach. Yuan et al. (2023) employed an ISM-DEMATEL approach to investigate the critical factors that influence illegal dumping behavior in construction industry. Xu et al. (2021) used a two-stage ISM–MICMAC methodology to explore the barriers of blockchain technology adoption in the construction industry. Iqbal et al. (2023) examined the critical success factors of energy-efficient supply chains in the construction industry by integrating the Delphi, ISM, and MICMAC method. Fan et al. (2022) used an integrated ISM–MICMAC approach to assess the scheduling-related risk in the construction of prefabricated buildings. Thereby, multi-criteria analysis is postulated as a powerful tool to aid decision-makers in better selecting their options in a wide range of construction problems.

2.3. Identification of IoT adoption barriers in the construction industry

The technical, organizational and environmental (TOE) framework serves as the basis for factor identification because it can provide a more comprehensive framework of potential factors and is widely used to adopt information technologies. Reviewing the literature and considering expert opinions, some key barriers to IoT adoption in the construction industry have been identified. First, Scopus and Web of Science retrieved the relevant literature. The formula for the search string is as follows: "Internet of Things" AND "construction" OR "construction industry" OR "construction engineering" OR "construction management" OR "construction engineering and management." The search was conducted in May 2021. An initial literature search of the Scopus database yielded 3001 articles, while the Web of Science database had 2839 articles. Subsequently, 412 publications relevant to the present research question were retained through duplicate literature culling, browsing of literature titles and abstracts, and in-depth reading of the full text. We also collected data relevant to IoT from reports and other digital materials. Finally, a consensus on the barriers was achieved based on discussions and feedback from five industry experts and academics. During the process, "lack of training for employees" and "lack of awareness and understanding" were merged, and "the impediment of cultural habits" and "e-waste generation" were removed. Finally, 16 barriers to IoT adoption in the construction industry were identified and further categorized into economic, environmental, technological and organizational barriers in Table 1. These barriers are coded as VS1–VS16, respectively.

IoT refers to "smart objects connected to the Internet and communicating with each other with minimal or no human intervention" (K. K. Patel & S. M. Patel, 2016). In general, IoT is an environment or ecosystem in which smart objects (e.g., smartphones, sensors, wearable objects) are connected (Khan & Salah, 2018). These smart objects are

Table 1. Summary of IoT adoption barriers

Code	Barriers	Main references
a. Technological barriers		
VS1	Interoperability and standardization	Gamil et al. (2020), Oke et al. (2022b), Tang et al. (2019), Wang et al. (2019)
VS2	Scalability issues	Oke et al. (2022b), Wang et al. (2019)
VS3	Security and privacy issues	Gamil et al. (2020), Mahmud et al. (2018), Tang et al. (2019), Zhou and Ding (2017)
VS4	High energy consumption	Gubbi et al. (2013), Oke et al. (2022b), Wang et al. (2019)
VS5	Complexity of connected system design	Dave et al. (2016), Ibrahim et al. (2021), Oke et al. (2022b), Scuotto et al. (2016)
VS6	Issue of data centric	Gamil et al. (2020), Jia et al. (2019), Tang et al. (2019), Wang et al. (2019)
VS7	Inadequate infrastructure	Khatua et al. (2020), Oke et al. (2022b)
b. Organization barriers		
VS8	Lack of technology knowledge	Gamil et al. (2020), Ibrahim et al. (2021), Mahmud et al. (2018), Tang et al. (2019)
VS9	High cost	Gamil et al. (2020), Mahmud et al. (2018), Oke et al. (2022b), Tang et al. (2019)
VS10	Lack of collaboration	Gamil et al. (2020), Ghimire et al. (2017), Tang et al. (2019)
VS11	Lack of trust	Gamil et al. (2020), Janssen et al. (2019)
c. Organizational barriers		
VS12	Legal and regulatory uncertainty	Gamil et al. (2020), Ibrahim et al. (2021), Jia et al. (2019)
VS13	Industry resistance	Dave et al. (2016), Gamil et al. (2020)
VS14	Lack of validation and identification	Mahmud et al. (2018), Zhou and Ding (2017)
VS15	Complexity of construction process	Chang et al. (2019), Jia et al. (2019), Magruk (2015)
VS16	Lack of governance and top management support	Bennett et al. (2017), Ghosh et al. (2020)

always connected at all times and exchange data (I. Lee & K. Lee, 2015). Each smart object in IoT has different processing, information, and communication capabilities (Tang et al., 2019). Standardization is essential for two-way communication and information exchange between smart devices, environments, smart objects, and other systems (Albishi et al., 2017). This ensures the smooth integration between stakeholders and data. Connecting several different smart devices to the same network is a major challenge, as most of these devices run on different platforms and use different communication algorithms (Singh & Bhanot, 2020). IoT consists of multiple standards that cover different aspects from identification to communication. The potential benefits can only be realized through the homogenization of existing devices or the development of new open standards (Borgia, 2014). In previous studies, ensuring interoperability and the lack of standardization have been identified as the most common impediments for IoT adoption in the construction industry (Gamil et al., 2020; Oke et al., 2022b; Tang et al., 2019; Wang et al., 2019). As IoT network grows in size and is expected to connect more physical devices in the future, scalability will become an important issue (Oke et al., 2022b). For communication and services as a basic function, IoT requires new approaches and better functionality to operate in a scalable manner (Wang et al., 2019). Therefore, scalability issues have been identified as barriers to IoT adoption in the construction industry.

The huge flow of information on IoT platforms poses cyber security threats and data privacy issues (Gamil et al., 2020; Zhou & Ding, 2017). Working virtually on a server or platform requires employees to understand the principles of cybersecurity. Cybersecurity risks related to authentication, authorization, privacy, system access, applications, networks, and data remain the biggest impediments to IoT adoption in the construction industry (Mahmud et al., 2018; Tang et al., 2019). The power consumption of IoT devices is a serious issue. Devices with RFID, but without power, are the preferred choice for IoT implementation. As the demand for IoT devices continues to grow, the energy cost of the value chain is expected to increase. Power is an important issue in the application of IoT in the construction industry (Gubbi et al., 2013; Oke et al., 2022b; Wang et al., 2019). A large software infrastructure is required for backend servers and networks to manage intelligent objects efficiently. Scuotto et al. (2016) also explained that, in smart objects, software systems will have to operate with minimal resources, as in conventional embedded systems. Scholars suggest that IoT implementation is essentially a complex connected system design problem (Dave et al., 2016; Ibrahim et al., 2021; Oke et al., 2022a).

In the construction industry, IoT applications are typically engaged in collecting information and irregular communication from logistics or sensor networks. Large-scale networks collect large amounts of data on a central web server or node. Many operational mechanisms, as well as new technologies for processing, storing, and managing big data, are required. Large data capacity, inaccurate data, more complicated big data collection, processing and storage data management, and data mining. Extensive literature supports data-centric issues as a key barrier to IoT adoption (Gamil et al., 2020; Wang et al., 2019). Infrastructure in the construction industry has not matured sufficiently to extensively adopt new IoT technologies (Khatua et al., 2020). Poor Internet connectivity and power outages are common in the field. In the construction industry, not only do contractors need the Internet, but all construction supply chain partners must use it as well. Some partners are located in remote areas where low Internet penetration and problems with a constant power supply can affect the flow of real-time information (Oke et al., 2022b).

The shortage of professional talent has become a bottleneck that restricts the adoption of IoT. The biggest challenge for companies is overcoming the lack of digital culture and training (Ibrahim et al., 2021). Efficient design and deployment of IoT solutions require a wealth of essential knowledge across a variety of technical and non-technical disciplines. However, companies find it difficult to develop these competencies. At present, many IoT managers do not have comprehensive background knowledge, and many employees have not acquired the necessary knowledge of IoT (Gamil et al., 2020; Mahmud et al., 2018; Tang et al., 2019). Hence, a lack of technical knowledge is an important factor that hampers IoT adoption, as there is a discernible lack of experienced IoT experts in the construction industry. High cost refers to the capital expenditure that construction companies must incur in developing and maintaining IoT infrastructure. Owing to the limited technology and raw materials, the initial cost, maintenance cost, and all other costs associated with IoT are high (Gamil et al., 2020; Tang et al., 2019). Investments in emerging technologies (e.g., IoT) pose a significant threat, particularly for small and medium-sized construction companies, owing to the potential for financial loss and non-recovery of investments (Mahmud et al., 2018; Oke et al., 2022b; Wang et al., 2019).

Using an IoT solution requires the involvement of all the project partners (Gamil et al., 2020). Given that all data scanning, transmission, and information infrastructures need to integrate existing systems with IoT and require cooperation between all project partners. The current global construction enterprise that exists today involves many stakeholders belonging to different regions and at different levels of digital readiness. Sometimes stakeholders have different concepts of IoT and may not agree on the positive impact of an IoT-based transformation of the construction industry (Tang et al., 2019). Aligning business strategies and working with different stakeholders involves mutual commitment, and creating a common vision is a key challenge for successful IoT adoption (Ghimire et al., 2017). The stakeholders in the construction industry, such as owners, contractors, and suppliers, are skeptical about the use of IoT-based systems. Lack of trust between construction participants has been seen as a significant barrier to IoT adoption (Gamil et al., 2020; Janssen et al., 2019).

With increasing competition, digitalization poses a legal challenge. When deploying a digital strategy, laws regarding data protection and standardization must be considered (Gamil et al., 2020). Every business that uses IoT needs to ensure that the online transfer of data is done securely, that privacy regulations are not breached, and that contracts entered into are valid and enforceable (Ibrahim et al., 2021; Jia et al., 2019). The construction industry is a fragmented and conservative one that lacks the willingness to adopt new technologies and innovations. Dave et al. (2016) imply that the main barrier to IoT adoption stems from the fact that stakeholders in the construction industry are resistant to change, and highlight that the lack of IoT standards hinders companies from adopting changes in the construction industry. Gamil et al. (2020) further suggest that key players in Malaysia lack awareness of the benefits and resist change to remain successful in the industry. Due to this resistance to change, companies have failed to fully adopt and understand the benefits of IoT implementation (Ibrahim et al., 2021). Thus, resistance to change is an important challenge that companies must address before they can begin implementing an IoT framework.

Although many researchers have proposed ideas and frameworks for Internet systems, they have not yet been verified. The available literature on the improvement and development of IoT-based systems mainly addresses functional and technical challenges (Mahmud et al., 2018). Research on multiple applications in the industry is scarce and still in its infancy. Few IoT adoptions have shown clear payoffs across the industry, which may discourage small and independent commercial enterprises from adopting this disruptive and innovative technology (Zhou & Ding, 2017). The construction process consists of a series of complex and dynamic activities that prevent it from embracing revolutionary changes (Demirkesen & Tezel, 2021). The implementation of intelligent automation in construction needs to be compatible with existing designs, management capabilities, workforce practices, and field operations. The complex structures and processes of the construction industry have the potential to limit the successful adoption of IoT (Chang et al., 2019; Magruk, 2015). The fragmented, one-off, and uncertain nature of construction projects increases the difficulty of applying blockchain technology (Jia et al., 2019). Lack of governance and support from the top management is one of the fundamental barriers to IoT development for contractors, consultants, and developers. Alaloul et al. (2020) explored the challenges and opportunities of IR 4.0 and highlighted the lack of governance and support from top management as a key barrier to its implementation. Furthermore, Ghosh et al. (2020) also found that the main barriers to the implementation of IoT in the construction industry included the lack of governance and top management support. The construction industry typically works on a project basis, and most senior project managers currently lack governance and support in the adoption of emerging technologies (Bennett et al., 2017). As a result, the reluctance of the business owners to experiment with new technologies proves to be a major barrier to successful IoT adoption.

3. Research methodology

This research used hybrid approaches based on using two different MCDM methods: ISM and DEMATEL. The combination of ISM and DEMATEL works very well with a relatively small sample size (Xu et al., 2021). It has been proven that both the DEMATEL and ISM approaches are powerful techniques for capturing the complex relationships of the system (Debnath et al., 2017; Kumar & Dixit, 2018). The ISM approach can analyze the hierarchical impact relationship between the indicators in the system and establish a causal relationship model between the indicators, but it cannot quantify the degree of impact between indicators and indicators (Dos Muchangos et al., 2015). The DEMATEL approach cannot directly express the causal relationship between indicators, but it can analyze the relationship between influencing factors in detail (Gardas et al., 2018; Hassan & Asghar, 2021; Kumar & Dixit, 2018). Integrated ISM-DEMATEL has been widely used in various fields because combining these two methods can overcome the shortcomings of being used alone (Dos Muchangos et al., 2015). Moreover, ISM-DEMATEL can streamline mathematical operations and alleviate the workload on experts (Xu et al., 2021). By utilizing the output of ISM as input for DEMATEL, this approach allows experts to focus on assessing the level of influence among chosen factors, thereby enhancing the rationality of data collection and the effectiveness of results. The ISM-DEMATEL framework is shown in Figure 1.

3.1. ISM

ISM technology is a commonly used system analysis modelling method proposed by Warfield (1974). It aims to establish a multilevel structural model by decomposing the

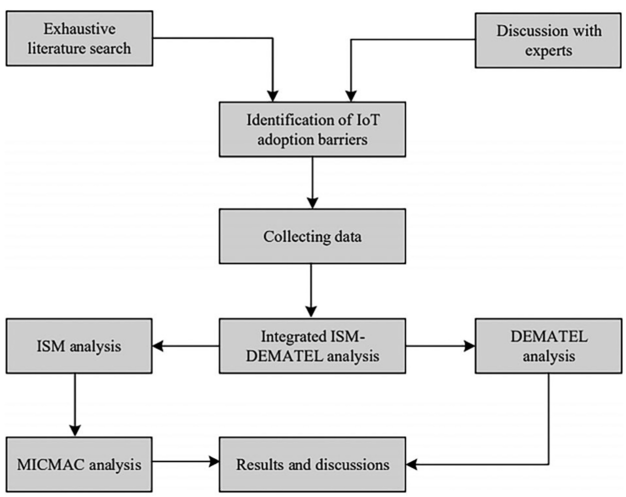

Figure 1. The integrated ISM-DEMATEL framework

different components of the system, assisted by expert experience and computer software. It is apt for combining qualitative and quantitative analysis methods to transform ambiguous system concepts that cannot be directly measured into a system architecture into an easy-to-analyze form, thereby providing a clearer interpretation of complex system problems. The specific steps of the ISM model are as follows:

Step 1: The key barriers to IoT adoption barriers are identified with the help of a literature review and expert opinions in the construction industry.

Step 2: A contextual relationship is established among the determined adoption barriers.

Step 3: Develop a structural self-interaction matrix (SSIM) based on the contextual relationship between variable pairs. "V", "A", "X", "O" are usually used to indicate different relationships between the variables.

Step 4: Convert SSIM to the initial reachability matrix (IRM). That is, convert symbols "V", "A", "O", and "X" into binary elements "0" and "1".

Step 5: Check the transferability of IRM to obtain the final reachability matrix (FRM).

Step 6: Divide FRM into different levels.

Step 7: Draw a directed graph and develop an ISM model.

3.2. MICMAC

Generally, ISM is followed by MICMAC analysis, invented by Duperrin and Godet (1973). MICMAC is based on matrix multiplication principles, where the ISM output serves as input to MICMAC. MICMAC analysis aims to recognize each construct's "driving and dependence power" and uses a categorization method to classify them accordingly. It is also an indirect method for classification to critically analyze each construct's complex scope (Khan & Haleem, 2012). Follow Bhosale and Kant (2016), the steps for MICMAC analysis are:

Step 1: "Binary direct relationship matrix (BDRM)" is acquired by considering all diagonal elements as zero, and rest are unchanged in the IRM matrix.

Step 2: Develop a "linguistic assessment direct reachability matrix".

Step 3: Develop a "MICMAC-stabilized matrix".

Step 4: Obtain each construct's "driving and dependence powers" and draw the MICMAC plot.

3.3. DEMATEL

Decision Making Trial and Evaluation Laboratory (DEMATEL) technique was carried out by the "Geneva Research Centre of the Battelle Memorial Institute" to understand a complex system's causal relationship structure through matrixes and digraphs. This method not only quantitatively analyzes the indicators in the system via the distribution diagram of the calculation results but also determines the main influencing factors in the system. The specific steps are as follows:

Step 1: Generate the direct influence matrix.

Step 2: Standardization of the direct relationship matrix.

Step 3: Establish a total relationship matrix.

Step 4: Calculate the degree of impact.

Step 5: Draw an impact diagram.

4. Research and data analysis

4.1. Data collection for quantifying barrier factors

To improve the validity of the questionnaire, a non-random sampling method was used to choose participants. We contacted experts attending large conferences on engineering management and micro-groups focusing on smart construction. These participants were usually middle and senior leaders and senior researchers in construction companies. They had a certain degree of knowledge and interest in IoT and its related technologies, due to their involvement in training and knowledge dissemination on IoT. Moreover, experts from various companies and departments were selected to ensure multidimensional access to information, thereby increasing the reliability of the data. To ensure data collection quality, participants should have good knowledge background or practical expertise in the field. Overall, a total of 39 experts were contacted in this study, of which 17 agreed to participate. The background information of the selected experts is presented in Table 2.

There were two rounds of data collection. In the first round, the selected experts were invited to score the barrier factors, and their responses were used in the next steps of the ISM analysis. The second round of data collection was initiated by contacting the 17 experts again to rate the relationships between barriers obtained from the ISM analysis.

Table 2. Statistics of expert background information

Category	Classification	Number
Highest education	Bachelor	2
	Master	9
	PhD	6
Working experience	Under 5 years	2
	5–10 years	3
	10–15 years	8
	More than 15 years	4
Organizational background	Owner company	2
	Construction company	5
	Consulting and service company	5
	Academics	5
Job position	Management positions	5
	Technical positions	6
	Management and technical positions	6

4.2. ISM analysis

4.2.1. SSIM development

"V", "A", "X", and "O" were used to define the contextual relationships between two barriers:

V: "VSi" leads to the achievement of "VSj". For example, interoperability and standardization (VS1) result in high energy consumption (VS4), while "VS4" does not affect "VS1". Therefore, "V" was used to define the relationship between "VS1" and "VS4".

A: "VSj" leads to the formation of "VSi". For example, interoperability and standardization (VS1) does not affect the complexity of the system (VS6), and "VS6" leads to "VS1". Therefore, "A" was used to define the relationship between "VS1" and "VS6".

X: "Fi" and "Fj" influence each other. For example, there is an interaction between interoperability and standardization (VS1) and scalability issues (VS2). Therefore, "X" was used to define the relationship between "VS1" and "VS2".

O: There is no influence between "VSi" and "VSj". For example, the scalability issue (VS2) does not affect the laws and regulations uncertainty (VS12), and "VS12" does not affect "VS2". Therefore, "O" was used to define the relationship between "VS2" and" VS12".

Therefore, the SSIM was constructed as shown in Table 3.

4.2.2. IRM and FRM development

Converted SSIM to IRM, namely, "V", "A", "X" and "O" be replaced with "0" or "1" during the process. The reachable matrix is a binary matrix that represents the direct connection state between the elements in the relationship graph. If the cell (i, j) of SSIM is "V", covert "1" in cell (i, j) and "0" in cell (j, i) of IRM. If the cell (i, j) of SSIM is "A", covert "0" in cell (i, j) and "1" in cell 1 (j, i). If the cell (i, j) of SSIM is "X", covert "1" in cells (i, j) and (j, i) of IRM. If the cell (i, j) of SSIM is "O", covert "0" in cells (i, j) and (j, i) of IRM. The result of IRM is shown in Table 4.

Next, we convert the IRM to FRM. The most critical step in generating an FRM is to check the transitivity in the IRM. Transitivity is a basic assumption of the ISM model; that is, if "VS1" is related to "VS2" and "VS2" is related to "VS3", then "VS1" and "VS3" must be related. In this case, "0" in the IRM should be replaced with "1^*", which indicates transitivity. After checking the transferability, the FRM was generated, as shown in Table 5.

4.2.3. Level partitioning

FRM can be used for level division. The level division is based on the reachability, antecedent, and interaction sets from the final reachability matrix. The reachability set consists of the factor itself and the other factors that it may reach. For example, the reachability set of "VS1" is [1, 2, 3, 4, 5, 9, 10, 11, 13, 14]. The antecedent word set consists of the factor itself along with other possible factors. For example, the antecedent word set of VS1 is [1, 2, 3, 5, 6, 7, 8, 12, 15, 16]. The interaction set is the intersection of the reachability and antecedent sets. In these sets, if the accessibility setting of an obstacle factor is the same as the interaction set, it is considered the top level of the hierarchy. Once the top factors are determined, they are removed from repeated iterations until all the factors are assigned to the appropriate levels. Table 6 presents the detailed iterative processes and results.

Table 3. SSIM

Code	VS16	VS15	VS14	VS13	VS12	VS11	VS10	VS9	VS8	VS7	VS6	VS5	VS4	VS3	VS2	VS1
VS1	A	A	V	V	A	V	V	V	A	A	A	X	V	X	X	
VS2	A	A	V	V	O	V	V	V	A	A	A	X	V	X		
VS3	A	A	V	V	O	V	V	V	A	A	A	X	V			
VS4	A	A	X	V	A	V	V	X	A	O	A	A				
VS5	A	A	V	O	A	V	V	V	A	A	A					
VS6	A	X	V	V	O	V	V	V	V	A						
VS7	X	V	V	V	V	O	V	V	O							
VS8	A	A	V	V	O	V	V	V								
VS9	A	A	V	V	O	A	A									
VS10	A	A	A	X	A	X										
VS11	A	A	A	X	A											
VS12	A	X	V	V												
VS13	A	A	X													
VS14	A	A														
VS15	A															
VS16																

Table 4. IRM

Code	VS1	VS2	VS3	VS4	VS5	VS6	VS7	VS8	VS9	VS10	VS11	VS12	VS13	VS14	VS15	VS16
VS1	1	1	1	1	1	0	0	0	1	1	1	0	1	1	0	0
VS2	1	1	1	1	1	0	0	0	1	1	1	0	1	1	0	0
VS3	1	1	1	1	1	0	0	0	1	1	1	0	1	1	0	0
VS4	0	0	0	1	0	0	0	0	1	1	1	0	1	1	0	0
VS5	1	1	1	1	1	0	0	0	1	1	1	0	0	1	0	0
VS6	1	1	1	1	1	1	0	1	1	1	1	0	1	1	1	0
VS7	1	1	1	0	1	1	1	0	1	1	0	1	1	1	1	1
VS8	1	1	1	1	1	0	0	1	1	1	1	0	1	1	0	0
VS9	0	0	0	1	0	0	0	0	1	0	0	0	1	1	0	0
VS10	0	0	0	0	0	0	0	0	1	1	1	0	1	0	0	0
VS11	0	0	0	0	0	0	0	0	1	1	1	0	1	0	0	0
VS12	1	0	0	1	1	0	0	0	0	1	1	1	1	1	1	0
VS13	0	0	0	0	0	0	0	0	0	1	1	0	1	1	0	0
VS14	0	0	0	1	0	0	0	0	0	1	1	0	1	1	0	0
VS15	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0
VS16	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Table 5. FRM

Code	VS1	VS2	VS3	VS4	VS5	VS6	VS7	VS8	VS9	VS10	VS11	VS12	VS13	VS14	VS15	VS16	Driving Power
VS1	1	1	1	1	1	0	0	0	1	1	1	0	1	1	0	0	10
VS2	1	1	1	1	1	0	0	0	1	1	1	0	1	1	0	0	10
VS3	1	1	1	1	1	0	0	0	1	1	1	0	1	1	0	0	10
VS4	0	0	0	1	0	0	0	0	1	1	1	0	1	1	0	0	6
VS5	1	1	1	1	1	0	0	0	1	1	1	0	1*	1	0	0	10
VS6	1	1	1	1	1	1	0	1	1	1	1	1*	1	1	1	0	14
VS7	1	1	1	1*	1	1	1	1*	1	1	1*	1	1	1	1	1	16
VS8	1	1	1	1	1	0	0	1	1	1	1	0	1	1	0	0	11
VS9	0	0	0	1	0	0	0	0	1	1*	1*	0	1	1	0	0	6
VS10	0	0	0	1*	0	0	0	0	1	1	1	0	1	1*	0	0	6
VS11	0	0	0	1*	0	0	0	0	1	1	1	0	1	1*	0	0	6
VS12	1	1*	1*	1	1	1*	0	1*	1*	1	1	1	1	1	1	0	14
VS13	0	0	0	1*	0	0	0	0	1*	1	1	0	1	1	0	0	6
VS14	0	0	0	1	0	0	0	0	1*	1	1	0	1	1	0	0	6
VS15	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	14
VS16	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	16
Dependence Power	10	10	10	16	10	5	2	6	16	16	16	5	16	16	5	2	

Table 6. Iterations for level partitions

Iteration No.	Code	Reachability set	Antecedent set	Interaction set	Level
Iteration 1	VS1	1, 2, 3, 4, 5, 9, 10, 11, 13, 14	1, 2, 3, 5, 6, 7, 8, 12, 15, 16	1, 2, 3, 5	
	VS2	1, 2, 3, 4, 5, 9, 10, 11, 13, 14	1, 2, 3, 5, 6, 7, 8, 12, 15, 16	1, 2, 3, 5	
	VS3	1, 2, 3, 4, 5, 9, 10, 11, 13, 14	1, 2, 3, 5, 6, 7, 8, 12, 15, 16	1, 2, 3, 5	
	VS4	4, 9, 10, 11, 13, 14	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16	4, 9, 10, 11, 13, 14	I
	VS5	1, 2, 3, 4, 5, 9, 10, 11, 13, 14	1, 2, 3, 5, 6, 7, 8, 12, 15, 16	1, 2, 3, 5	
	VS6	1, 2, 3, 4, 5, 6, 8, 9, 10, 11, 12, 13, 14, 15	6, 7, 12, 15, 16	6, 15	
	VS7	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16	7, 16	7, 16	
	VS8	1, 2, 3, 4, 5, 8, 9, 10, 11, 13, 14	6, 7, 8, 12, 15, 16	8	
	VS9	4, 9, 10, 11, 13, 14	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16	4, 9, 10, 11, 13, 14	I
	VS10	4, 9, 10, 11, 13, 14	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16	4, 9, 10, 11, 13, 14	I
	VS11	4, 9, 10, 11, 13, 14	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16	4, 9, 10, 11, 13, 14	I
	VS12	1, 2, 3, 4, 5, 6, 8, 9, 10, 11, 12, 13, 14, 15	6, 7, 12, 15, 16	6, 12, 15	
	VS13	4, 9, 10, 11, 13, 14	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16	4, 9, 10, 11, 13, 14	I
	VS14	4, 9, 10, 11, 13, 14	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16	4, 9, 10, 11, 13, 14	I
	VS15	1, 2, 3, 4, 5, 6, 8, 9, 10, 11, 12, 13, 14, 15	6, 7, 12, 15, 16	6, 12, 15	
	VS16	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16	7, 16	16	
Iteration 2	VS1	1, 2, 3, 5	1, 2, 3, 5, 6, 7, 8, 12, 15, 16	1, 2, 3, 5	II
	VS2	1, 2, 3, 5	1, 2, 3, 5, 6, 7, 8, 12, 15, 16	1, 2, 3, 5	II
	VS3	1, 2, 3, 5	1, 2, 3, 5, 6, 7, 8, 12, 15, 16	1, 2, 3, 5	II
	VS5	1, 2, 3, 5	1, 2, 3, 5, 6, 7, 8, 12, 15, 16	1, 2, 3, 5	II
	VS6	1, 2, 3, 5, 6, 8, 12, 15	6, 7, 12, 15, 16	6, 12, 15	
	VS7	1, 2, 3, 5, 6, 7, 8, 12, 15, 16	7, 12, 16	7, 12, 16	
	VS8	1, 2, 3, 5, 8	6, 7, 8, 12, 15, 16	8	
	VS12	1, 2, 3, 5, 6, 8, 12, 15	7, 12, 16	12	
	VS15	1, 2, 3, 5, 6, 8, 12, 15	6, 7, 12, 15, 16	6,1 2, 15	
	VS16	1, 2, 3, 5, 6, 7, 8, 12, 15, 16	7, 16	7, 16	
Iteration 3	VS6	6, 8, 12, 15	6, 7, 12, 15, 16	6, 12, 15	
	VS7	6, 7, 8, 12, 15, 16	7, 12, 15, 16	7, 12, 15, 16	
	VS8	8	6, 7, 8, 12, 15, 16	8	III
	VS12	6, 8, 12, 15	6, 7, 12, 16	6, 12	
	VS15	6, 8, 12, 15	6, 7, 12, 15, 16	6, 12, 15	
	VS16	6, 7, 8, 12, 15, 16	7, 16	7, 16	
Iteration 4	VS6	6, 12, 15	6, 7, 12, 15, 16	6, 12, 15	IV
	VS7	6, 7, 12, 15, 16	7, 12, 15, 16	7, 12, 15, 16	
	VS12	6, 12, 15	6, 7, 12, 15, 16	6, 12, 15	IV
	VS15	6, 12, 15	6, 7, 12, 15, 16	6, 12, 15	IV
	VS16	6, 7, 12, 15, 16	7, 16	7, 16	
Iteration 5	VS7	7, 16	7, 16	7, 16	V
	VS16	7, 16	7, 16	7, 16	V

4.2.4. ISM model

Based on the hierarchical division results and FRM, a detailed ISM model is established, as shown in Figure 2. The 16 barriers were divided into five levels. The relationship between barriers is indicated by the directed arrows, and two-way arrows indicate mutual influence. The resulting graph is called a directed graph.

4.3. MICMAC analysis

To better understand the driving forces and influence of the barriers to the adoption of IoT in the construction industry, MICMAC analysis was adopted. Convert FRM into the MICMAC graph (see Figure 3). The MICMAC diagram divides the 16 key obstacles into four clusters: autonomous, dependent, linkage, and driving (Kannan & Haq, 2007). As shown in Figure 3, the MICMAC analysis shows that there is no barrier factor variable in the autonomous cluster, which means that the barrier factors selected for research are sufficient to reveal the research results. VS7, VS16, VS6, VS12, VS15, VS8, VS11, VS7, and VS5 are located in the driving cluster, which shows that their driving force is high while the dependence is weak. VS4, VS9, VS10, VS11, VS13, and VS14 are all in the dependency cluster, indicating that they have a higher dependency and a weaker driving force. The other obstacles are in the link cluster, which means that they have a stronger driving force and higher dependence. In general, if a certain obstacle factor has a highly dependent characteristic, other obstacles must be overcome before removing the obstacle. Because the obstacles with high driving forces are solved first, it is conducive to the solution of other obstacles.

4.4. DEMATEL analysis

To better understand the causal relationship and mutual influence between the identified obstacle factors, the DEMATEL method was adopted.

4.4.1. Average direct influence matrix

The output of the ISM is used as the input for the DEMATEL in this study. Therefore, the same group of experts who were consulted for the ISM was selected for data collection. The experts rated the relationship between obstacles on a scale of 0–4 based on the influence of one obstacle on other obstacles. Through data aggregation, the average direct influence matrix was obtained, as shown in Table 7.

4.4.2. Normalized average direct influence matrix

The average direct influence matrix was normalized, and the results are listed in Table 8.

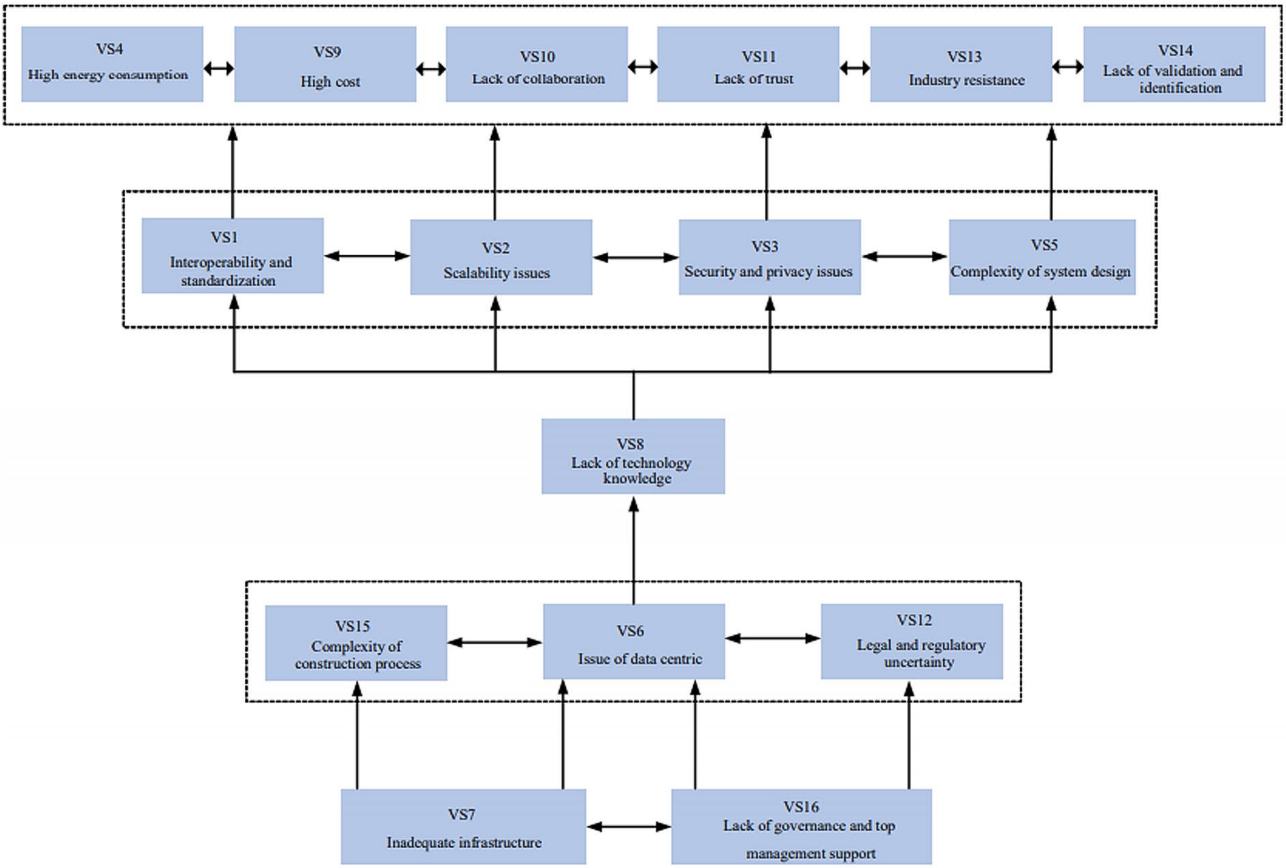

Figure 2. ISM-based model of IoT adoption barriers in the Chinese construction industry

4.4.3. Total relation matrix

The total relationship matrix (T) was calculated using the formula $T = N(I - N)^{-1}$, where N represents the normalized average direct relationship matrix, and I represent the identity matrix. In addition, the sum of the rows and columns of the total relationship matrix and the threshold (λ) were calculated. The results are listed in Table 9.

4.4.4. Degree of influence and causality diagram

Based on the results of the total relationship matrix, the importance of each factor and the causal relationship between them were calculated. The value corresponding to Cj is the sum of a certain column in the total relationship matrix, and the value corresponding to Ri is the sum of a certain row in the total relationship matrix. Cj + Ri stands for "outstanding value" which indicates the overall impact of the corresponding obstacle factor on the entire system. Based on the results, the 16 factors were ranked in order of importance. Ri – Cj stands for "relationship value" and the barriers are divided into cause-and-effect groups with positive and negative values, respectively. The results are listed in Table 10. Based on these data, an impact diagram was drawn in Figure 4.

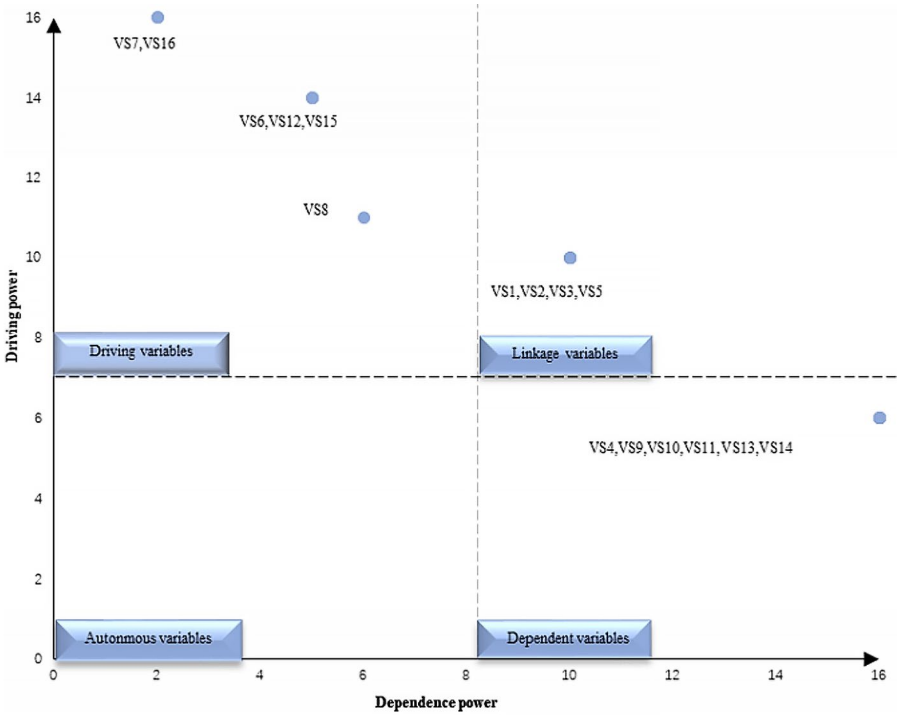

Figure 3. MICMAC analysis results

Table 7. Average direct influence matrix

Code	VS1	VS2	VS3	VS4	VS5	VS6	VS7	VS8	VS9	VS10	VS11	VS12	VS13	VS14	VS15	VS16
VS1	0.000	1.765	0.941	0.882	0.882	0.000	0.000	0.000	1.353	1.882	1.176	0.000	2.412	2.059	0.000	0.000
VS2	1.176	0.000	1.000	0.941	1.059	0.000	0.000	0.000	2.471	2.059	2.059	0.000	2.941	2.000	0.000	0.000
VS3	0.824	1.118	0.000	0.882	0.882	0.000	0.000	0.000	2.412	2.176	2.824	0.000	2.824	2.118	0.000	0.000
VS4	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.765	1.824	1.824	0.000	2.471	2.059	0.000	0.000
VS5	0.882	1.118	1.059	1.118	0.000	0.000	0.000	0.000	1.412	1.941	1.471	0.000	1.235	0.941	0.000	0.000
VS6	0.882	1.118	1.000	1.118	0.765	0.000	0.000	1.235	1.529	2.000	1.059	0.941	1.294	1.000	0.824	0.000
VS7	1.647	3.118	1.412	1.000	0.882	1.118	0.000	1.176	3.118	2.294	1.235	0.706	1.706	2.059	0.882	0.647
VS8	1.941	1.941	2.059	1.941	2.118	0.000	0.000	0.000	1.059	3.059	1.529	0.000	2.824	0.882	0.000	0.000
VS9	0.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000	2.059	0.941	0.000	1.353	2.765	0.000	0.000
VS10	0.000	0.000	0.000	0.588	0.000	0.000	0.000	0.000	2.176	0.000	1.118	0.000	1.471	1.059	0.000	0.000
VS11	0.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000	1.824	2.941	0.000	0.000	1.294	1.118	0.000	0.000
VS12	1.882	1.118	0.941	1.118	0.941	1.000	0.000	0.882	1.176	1.176	2.529	0.000	2.176	1.059	1.412	0.000
VS13	0.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000	1.294	2.588	0.941	0.000	0.000	2.824	0.000	0.000
VS14	0.000	0.000	0.000	1.235	0.000	0.000	0.000	0.000	1.000	1.118	2.118	0.000	1.647	0.000	0.000	0.000
VS15	2.353	2.118	1.765	1.882	2.118	1.882	0.000	3.118	2.765	1.529	1.059	3.118	1.588	1.941	0.000	0.000
VS16	0.941	0.882	1.000	0.941	0.941	0.941	2.824	1.941	0.882	2.000	1.000	0.882	1.882	1.118	1.000	0.000

Table 8. Normalized average direct influence matrix

Code	VS1	VS2	VS3	VS4	VS5	VS6	VS7	VS8	VS9	VS10	VS11	VS12	VS13	VS14	VS15	VS16
VS1	0.000	0.058	0.031	0.029	0.029	0.000	0.000	0.000	0.044	0.061	0.038	0.000	0.079	0.067	0.000	0.000
VS2	0.038	0.000	0.033	0.031	0.035	0.000	0.000	0.000	0.081	0.067	0.067	0.000	0.096	0.065	0.000	0.000
VS3	0.027	0.036	0.000	0.029	0.029	0.000	0.000	0.000	0.079	0.071	0.092	0.000	0.092	0.069	0.000	0.000
VS4	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.058	0.060	0.060	0.000	0.081	0.067	0.000	0.000
VS5	0.029	0.036	0.035	0.036	0.000	0.000	0.000	0.000	0.046	0.063	0.048	0.000	0.040	0.031	0.000	0.000
VS6	0.029	0.036	0.033	0.036	0.025	0.000	0.000	0.040	0.050	0.065	0.035	0.031	0.042	0.033	0.027	0.000
VS7	0.054	0.102	0.046	0.033	0.029	0.036	0.000	0.038	0.102	0.075	0.040	0.023	0.056	0.067	0.029	0.021
VS8	0.063	0.063	0.067	0.063	0.069	0.000	0.000	0.000	0.035	0.100	0.050	0.000	0.092	0.029	0.000	0.000
VS9	0.000	0.000	0.000	0.033	0.000	0.000	0.000	0.000	0.000	0.067	0.031	0.000	0.044	0.090	0.000	0.000
VS10	0.000	0.000	0.000	0.019	0.000	0.000	0.000	0.000	0.071	0.000	0.036	0.000	0.048	0.035	0.000	0.000
VS11	0.000	0.000	0.000	0.033	0.000	0.000	0.000	0.000	0.060	0.096	0.000	0.000	0.042	0.036	0.000	0.000
VS12	0.061	0.036	0.031	0.036	0.031	0.033	0.000	0.029	0.038	0.038	0.083	0.000	0.071	0.035	0.046	0.000
VS13	0.000	0.000	0.000	0.033	0.000	0.000	0.000	0.000	0.042	0.084	0.031	0.000	0.000	0.092	0.000	0.000
VS14	0.000	0.000	0.000	0.040	0.000	0.000	0.000	0.000	0.033	0.036	0.069	0.000	0.054	0.000	0.000	0.000
VS15	0.077	0.069	0.058	0.061	0.069	0.061	0.000	0.102	0.090	0.050	0.035	0.102	0.052	0.063	0.000	0.000
VS16	0.031	0.029	0.033	0.031	0.031	0.031	0.092	0.063	0.029	0.065	0.033	0.029	0.061	0.036	0.033	0.000

Table 9. Total relation matrix

Code	VS1	VS2	VS3	VS4	VS5	VS6	VS7	VS8	VS9	VS10	VS11	VS12	V13	V14	V15	V16	Row total
VS1	0.004	0.060	0.034	0.047	0.032	0.000	0.000	0.000	0.075	0.097	0.066	0.000	0.109	0.100	0.000	0.000	0.625
VS2	0.041	0.005	0.035	0.052	0.037	0.000	0.000	0.000	0.113	0.109	0.096	0.000	0.128	0.105	0.000	0.000	0.720
VS3	0.029	0.039	0.003	0.050	0.031	0.000	0.000	0.000	0.112	0.114	0.120	0.000	0.125	0.108	0.000	0.000	0.732
VS4	0.000	0.000	0.000	0.013	0.000	0.000	0.000	0.000	0.076	0.084	0.075	0.000	0.097	0.089	0.000	0.000	0.434
VS5	0.031	0.040	0.037	0.051	0.003	0.000	0.000	0.000	0.072	0.093	0.070	0.000	0.068	0.060	0.000	0.000	0.526
VS6	0.040	0.048	0.042	0.060	0.035	0.003	0.000	0.044	0.087	0.109	0.069	0.034	0.084	0.073	0.029	0.000	0.757
VS7	0.070	0.118	0.061	0.070	0.045	0.040	0.002	0.045	0.159	0.144	0.094	0.028	0.121	0.130	0.032	0.021	1.182
VS8	0.070	0.073	0.074	0.089	0.076	0.000	0.000	0.000	0.083	0.154	0.091	0.000	0.141	0.081	0.000	0.000	0.932
VS9	0.000	0.000	0.000	0.042	0.000	0.000	0.000	0.000	0.017	0.084	0.046	0.000	0.060	0.105	0.000	0.000	0.354
VS10	0.000	0.000	0.000	0.028	0.000	0.000	0.000	0.000	0.081	0.018	0.047	0.000	0.059	0.052	0.000	0.000	0.285
VS11	0.000	0.000	0.000	0.042	0.000	0.000	0.000	0.000	0.075	0.112	0.015	0.000	0.058	0.056	0.000	0.000	0.357
VS12	0.073	0.051	0.043	0.065	0.043	0.036	0.000	0.035	0.084	0.094	0.119	0.006	0.118	0.083	0.047	0.000	0.896
VS13	0.000	0.000	0.000	0.043	0.000	0.000	0.000	0.000	0.059	0.101	0.047	0.000	0.019	0.107	0.000	0.000	0.375
VS14	0.000	0.000	0.000	0.048	0.000	0.000	0.000	0.000	0.048	0.056	0.079	0.000	0.067	0.019	0.000	0.000	0.317
VS15	0.101	0.095	0.080	0.107	0.090	0.065	0.000	0.108	0.156	0.136	0.103	0.104	0.134	0.136	0.007	0.000	1.422
VS16	0.051	0.055	0.051	0.065	0.048	0.038	0.092	0.073	0.086	0.130	0.080	0.036	0.119	0.092	0.038	0.002	1.057
Column Total	0.511	0.583	0.461	0.873	0.440	0.182	0.094	0.306	1.382	1.637	1.214	0.208	1.508				

5. Results and discussion

5.1. Results discussion

This study uses a hybrid ISM-DEMATEL research methodology to investigate the barriers to IoT adoption in the construction industry, exploring the hierarchical structure of the barriers and their interdependencies. The research results are impressive, as they reveal five different levels to describe the relationship between the barrier factors. The first level includes high energy consumption (VS4), high cost (VS9), lack of collaboration (VS10), lack of trust (VS11), industry resistance (VS13), and lack of validation and identification (VS14), which are driven by the four hierarchies below them. The second level includes interoperability and standardization issues (VS1), scalability issues (VS2), security and privacy issues (VS3), and complexity of system design (VS5), which are further driven by the three hierarchies below them. The third level includes a lack of technological knowledge (VS8). The fourth level includes the complexity of the construction process (VS15), the issue of data-centric (VS6), and legal and regulatory uncertainty (VS12). Level five includes inadequate infrastructure (VS7) and lack of governance and top management support (VS16), which are the strongest drivers.

Table 10. Degree of influence

Code	Cj	Ri	Cj + Ri	Ri – Cj	Rank based on Cj + Ri	Group
VS1	0.511	0.625	1.136	0.114	5	Cause
VS2	0.583	0.720	1.303	0.137	9	Cause
VS3	0.461	0.732	1.194	0.271	6	Cause
VS4	0.873	0.434	1.308	–0.439	10	Effect
VS5	0.440	0.526	0.966	0.087	2	Cause
VS6	0.182	0.757	0.938	0.575	1	Cause
VS7	0.094	1.182	1.276	1.087	8	Cause
VS8	0.306	0.932	1.238	0.625	7	Cause
VS9	1.382	0.354	1.736	–1.028	14	Effect
VS10	1.637	0.285	1.922	–1.353	16	Effect
VS11	1.214	0.357	1.571	–0.858	11	Effect
VS12	0.208	0.896	1.104	0.688	4	Cause
VS13	1.508	0.375	1.883	–1.133	15	Effect
VS14	1.395	0.317	1.712	–1.079	13	Effect
VS15	0.152	1.422	1.574	1.270	12	Cause
VS16	0.023	1.057	1.080	1.034	3	Cause

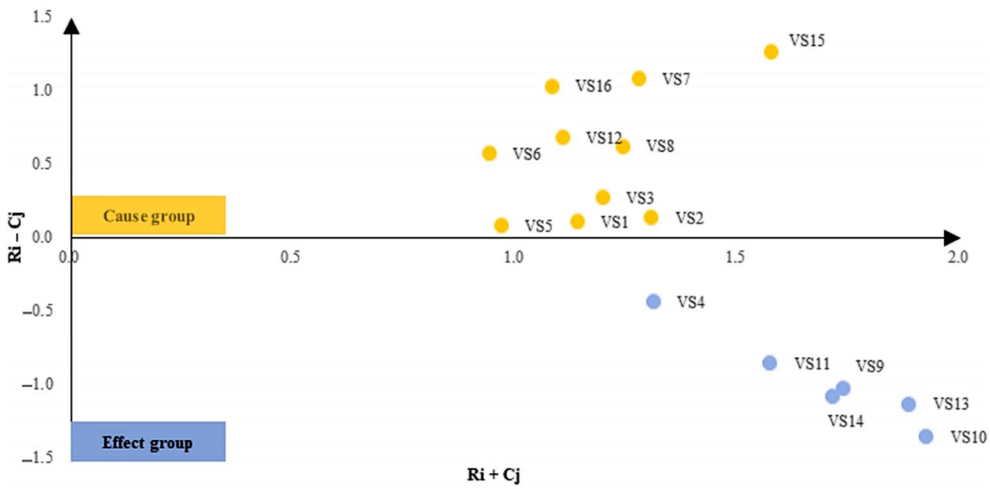

Figure 4. Influence relation diagram

From the model (see Figure 2), it is clear that inadequate infrastructure (VS7) and lack of governance and top management support (VS16) are the most important barriers to the adoption of IoT in the construction industry and thus, should be of serious concern to practitioners in the construction industry practitioners. Ghosh et al. (2019) and Ibrahim et al. (2021) also proved that these two structures are the main barriers to IoT adoption in the construction industry. The reason for this may be related to the characteristics of the construction industry, which is notorious for its low level of innovation and the slow adoption of new technologies. In group discussions of factor identification, construction practitioners also highlighted that, in addition to inadequate infrastructure, the more critical issue is that they do not know how to start, especially in the case of small and medium-sized organizations. As IoT adoption is still in its infancy, governments are not yet aware of promising application areas for IoT. This supports the findings in other industries of Singh and Bhanot (2020) and Janssen et al. (2019) that the institution environment is an important tool for enhancing IoT adoption. Furthermore, the research findings do not correspond with Calafat-Marzal et al. (2023). The reason may be that this data was obtained from China, where the development of IoT is still in its infancy and needs to rely on formalized rules. Other challenges arise when governments and organizations themselves are unable to encourage industry stakeholders to adopt IoT technology. The lack of well-framed norms and unclear value propositions hinders IoT adoption in the construction industry and further increases the complexity of project adoption. Furthermore, technology-related issues are amplified by the limited understanding of IoT among construction practitioners. This finding correspond with that of a previous research, which indicates that technical factors have a complicated influence on the technology adoption of IoT (Lin et al., 2016). These exacerbate the resistance to change, lack of trust among stakeholders, and difficulty in building collaborative networks. It presents a response to Khurshid et al. (2023), who called for studying the factors of IoT adoption in the construction industry through a comprehensive and extensive approach. Previous findings showed that several barriers to IoT adoption; however, these studies almost based on qualitative analysis (Khurshid et al., 2023; Salvi & Doctor, 2022). The results of this research further provide new quantitative evidence that these barriers and their interdependent relationships in the context of the AEC industry.

The MICMAC analysis showed that the selected VSs could be divided into three clusters. The autonomous cluster does not contain any VS, indicating that the selected VS in this study significantly influences or hinders IoT adoption in the construction industry. VS7, VS16, VS6, VS12, VS15, VS8, VS11, VS7, and VS5 were located in the driving cluster. Practitioners in the construction industry and decision-makers in the relevant sectors should pay attention to these factors and consider them the most important barriers. This is because changes in each of these factors can impact other factors at various levels.VS4, VS9, VS10, VS11, VS13, and VS14 are in the dependency cluster. These barriers should also be focused on because they have a high dependency capability, so the barriers affecting them should be removed before eliminating them to increase the probability of successful adoption.VS1, VS2, VS3, and VS5 are in the linkage cluster. These factors are quite sensitive because they are highly dependent and driven. Any change in these barriers affects other barriers at different levels and generates feedback.

Results of the ISM method results indicate the interdependence among all VSs, but the strength of the relationship is not available. The DEMATEL method can accurately track the strength of the relationships between the identified structures. Table 10 and Figure 4 show that the barriers were divided into causal groups. VS1, VS2, VS3, VS12, VS5, VS6, VS7, VS8, VS15, and VS16 belong to the cause group, and VS11, VS4, VS13, VS14, VS9, and VS10 belong to the effect group. The cause group factors have the potential to drive other factors, whereas the effect group factors depend on the cause group factors. For example, VS15, VS7, and VS16 affect many other factors, but other factors rarely influence them. In contrast, VS10 and VS13 are mainly influenced by other factors and rarely influence other factors. In addition, the 11 barriers were prioritized according to the salience value (Ri + Cj) with the following relationship: VS6 > VS5 > VS16 > VS12 > VS1 > VS3 > VS8 > VS7 > VS2 > VS4 > VS11 > VS15 > VS14 > VS9 > VS13 > VS6, which is the first hindering factor with a value of 0.938, followed by VS5 and VS16. The salient value represents the total causality. The higher the value, the more prominent the overall relationship between the particular factor and other factors. Although VS5 and VS6 are not high drivers, their overall causality in the framework of this study is very strong; therefore, these factors should also be given high priority.

5.2. Theoretical implications

This study provides three theoretical contributions to this field. First, this research has determined the barriers to IoT adoption in the construction industry, which extends the TOE framework to smart construction. Second, it is one of the first studies that use an integrated ISM-DEMATEL approach to derive a framework for the barriers to IoT adoption in the construction industry context. This research design and methodology can be used to understand the different determinants of other emerging technologies, such as artificial intelligence, blockchain, and digital twins. Finally, the driving and dependency capabilities of IoT barriers determined using the MICMAC diagram and the size of the relationship using DEMATEL help to enhance the understanding of the multifaceted and interdependent relationship of the barriers to IoT adoption. The purpose of constructing the ISM model is to obtain a hierarchy of barriers to IoT adoption that will allow practitioners and academics in the construction industry to understand their interdependencies quickly and clearly. This information will help practitioners and policymakers develop appropriate strategies for the successful adoption of IoT in the construction industry.

5.3. Managerial implications

Research insights help practitioners and stakeholders in the construction industry deepen their understanding of the barriers to implementing IoT, rather than addressing the challenges in isolation. Decision-makers can design effective frameworks and strategies for IoT practices based on the new ISM-DEMATEL results to reduce the complexity of IoT adoption process. First, the lack of management support and governance has been identified as the most critical barrier to adopting IoT. In this case, the role of top-level management is crucial for incorporating IoT. Although it is acceptable that, initially, IoT practices require more financial support, it will reap benefits in the long run. Hence, management must understand the significance of IoT adoption and invest in the latest cutting-edge technologies to progressively develop IoT implementation. The lack of infrastructure is another important barrier to IoT adoption. Organizations must have adequate and capable infrastructure to successfully implement an IoT environment, such as reliable high-speed connectivity, uninterrupted energy supply, and an IoT architecture for realizing cyber-physical systems in the building environment. It is the most important factor and is crucial in successfully implementing IoT. Unless this barrier is mitigated, a focus on mitigating other barriers may not be effective. Therefore, organizations must follow the necessary steps to remove these barriers, as they can lead to ineffective implementation of IoT in the construction industry. Finally, while ISM-DEMATEL frameworks were developed in the context of the Chinese construction industry, they also provide valuable references for other countries seeking to investigate barriers to IoT adoption to avoid the consequences of failure.

6. Conclusions and limitations

This study explored the barriers to adopting IoT in the Chinese construction industry. Sixteen key barriers were identified and determined through an extensive literature search and feedback from industry experts. Furthermore, these barriers were modelled using an integrated ISM-DEMATEL approach. An ISM model was constructed to assess the hierarchical structure between the impediments and thus identify the underlying impediments. The DEMATEL approach was used to estimate the strength of the relationships between them and determine the causal relationships. A MICMAC analysis was performed to identify and cluster the driving and dependency capabilities. The findings revealed that the barriers to IoT adoption are complex and hierarchical. Lack of governance, top management support, inadequate infrastructure, and complex building processes are the most critical barriers to IoT adoption in the construction industry. Therefore, the long-term development of IoT must augment top management support and strengthen IoT infrastructure. The uncertainty in laws and regulations, data-centric issues, lack of technical knowledge, interoperability and standardization issues, scalability issues, security and privacy issues, and system design complexity are other significant barriers that should be crossed with effective measures. These ten potential factors directly hinder IoT adoption in the construction industry.

This study has two main limitations. First, the ISM-DEMATEL analysis is based on the experience and knowledge of experts; thus, subjective bias is inevitable. Future research should collect more data and use structural equation models to verify the model statistically. Second, the questionnaire has been attempted only by Chinese construction practitioners and researchers, resulting in certain limitations in the results. In the future, we will consider collecting data from developed countries to compare and analyze the conclusions.

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Author contributions

Mengyuan CHENG and Guoliang LIU conceived the study and were responsible for the design and development of the data analysis. Yongshun XU and Ming CHI were responsible for data collection and analysis.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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