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A new perspective to evaluate the antecedent path of adoption of digital technologies in major projects of construction industry: A case study in China

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A R T I C L E I N F O

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DOI (diffusion of innovation)
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A B S T R A C T

The adoption of digital technologies is key to the digital transformation of the construction industry. However, the current adoption of digital technologies is limited. This study uses China as a case, combines the DOI and TOE theories to identify impact factors of the adoption of digital technologies in major projects. The configuration analysis is complemented with fuzzy-set qualitative comparative analysis. As a result, the study constructs the "TOE-D Technology Adoption Antecedent Framework", including 11 antecedents, and identifies three distinct configurations types, namely: "Needs-Resource-Collaboration"; "Resource" under high competitive pressure; and "Resource" under low competitive pressure. Comparing the configurations horizontally, the core or edge characteristics of factor in configurations are analyzed. The results can help major projects in the construction industry to ascertain a combination of elements, which promote the adoption of digital technologies so that project practitioners can make targeted and precise adjustments to enable digital transformation of the construction industry.

1. Introduction

In recent years, the digital economy has become a new engine of global economic growth, thereby driving the development of the real economy and providing a new impetus for the development of many economies around the world (Craveiro et al., 2019). As the foundation of the digital economy, the real economy also provides a multi-faceted underpinning for the development of the digital economy. In this context, we are currently witnessing a progressive integration of real economies with digital economies and the combination of digital technologies and material production processes related to traditional industries has brought continuous and subversive changes to various industries (Craveiro et al., 2019).

In particular, the application of digital technology in the construction industry has helped construction enterprises improve quality and efficiency, while completely subverting current construction methods. And it is an important engine for improving the level and quality of construction and promoting the transformation and wider upgrading of the construction industry. These digital technologies include big data, cloud computing, the Internet of Things, blockchain, and artificial intelligence (Wang and Li, 2022). Yet, at present, there is no unified definition of digital technology. In this regard, Tian and Li (2022) pointed out that the essence of digital technology is to realize the functions of identification, transformation, storage, dissemination, and application of various types of information. Whereas Yan and Shan Xiao (Yan and Shan Xiao, 2020) and Whyte (2019) identified that digital technologies refer to the conversion of information that cannot be recognized by computers, such as pictures, sounds, and words into code that can be recognized (that is, digital information). Thus, digital information enables large storage capacities, fast transmission speeds, and diversified processing methods; and digital information can be shared, accessed remotely, searched, and kept up-to-date in new ways. Furthermore, Goldfarb and Tucker (2019) illustrated that digital technologies help realize unlimited replication and sharing of data and real-time interconnection. Furthermore, digital technologies have unique advantages in reducing data processing and transaction costs;

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accurately allocating resources; and have major consequences for the flow of data, information and knowledge and hence the organization of work on projects (Whyte and Levitt, 2011).

The three international organizations of the Group of Twenty (G20), Organization for Economic Co-operation and Development (OECD) (é CONOMIQUES O D C E D D, 2017) (Andrews et al., 2018) and United Nations Conference on Trade and Development (UNCTAD) (Trade U N C O and Development, 2017) have all paid particular attention to more than a dozen representative digital technologies. But the main ones that have received most attention are artificial intelligence, blockchain, big data, cloud computing, and the Internet of Things. Whereas BIM (building information modeling) technology is the most widely used digital technology in the construction industry (Miettinen and Paavola, 2014). Therefore, the digital technologies investigated in this study are as follows: BIM, artificial intelligence, blockchain, big data, cloud computing, and the Internet of Things.

As a pillar industry of the Chinese economy, the digital transformation of the construction industry represents a key route for the sustainable and high-quality development of the sector. The adoption of digital technology also provides strong technical support for the digital transformation of the construction industry. For example, BIM technology synchronizes building construction status and real-time data management. This can play an important role in promoting cost control, construction progress management, and production efficiency improvement. Big data technology can effectively collect, integrate and manage the data information generated in project construction to ensure the efficiency of project construction (Huang et al., 2021). The cloud computing system integrates and allocates existing resources, such as construction, design, supervision, quality control, and material supply, avoiding duplication and waste of resources. IoT technology realizes intelligent identification, operation and management functions (Al-Fuqaha et al., 2015). Whereas blockchain technology offers a more streamlined procurement process. It can reduce the highly fragmented and complex nature of projects; revolutionize construction contracts and payment methods; and enable automated, secure and instant payment through smart contracts. Finally, it also has a great potential for building information transparency, quality traceability, secure payments, and collaboration and trust throughout the construction supply chain (Hamledari and Fischer, 2021a). Artificial intelligence can improve the level of refinement of the engineering field in various aspects at all stages of engineering projects (Abioye et al., 2021). At present, the construction industry has achieved outstanding progress in construction practice and this includes the delivery of many major projects, but the adoption of digital technologies is still lagging behind engineering practice (Liu et al., 2019). Moreover, the low level of digitalization of the construction industry remains a pressing issue (Liu et al., 2019). Indeed, the McKinsey Global Institute's report "*Imagining construction's digital future*" identifies that in the global industry digitalization index, the level of digital adoption in the construction industry is only higher than that of agriculture, ranking second to last. This lack of digitalization capability greatly affects the development of the construction industry and the digital development of the industry, and therefore, it has a long way to go.

Given the low degree of digitalization in the construction industry, scholars have carried out extensive research on the obstacles and factors influencing the adoption of digital technologies. For example, Nnaji (Nnaji et al., 2018) found that BIM, IoT (Internet of Things), RFID (radio-frequency identification), drones, and VR (virtual reality) technologies enable safer construction production and management. The results also showed that potential cost savings, technical effectiveness, reliability, and ease of use are all key factors influencing the adoption of digital technologies. Chaveesuk (Chaveesuk et al., 2020) evaluated the needs and influencing factors of stakeholders using blockchain-based smart contracts in construction. The study identified that certain factors, such as perceived financial costs, convenience, trust, and readiness, significantly affect the intent of the construction industry to use digital technologies. Among the digital technologies adopted in the construction industry, BIM technology is arguably one of the most common (Miettinen and Paavola, 2014). While other technologies remain in their infancy, research on BIM technology in the construction industry has been quite prolific (Bilal et al., 2016). Likewise, many scholars have researched the influencing factors of the adoption of BIM technology. Zhang (Zhang et al., 2020), for example, evaluated the factors affecting the adoption of BIM technology in construction companies. According to the theory of innovation diffusion, Chen and Ni (2019) investigated the diffusion barriers of BIM technology in China. Other researchers also identified many other aspects, such as the lack of uniformity, insufficient motivation (Ji et al., 2014), or unresolved connectivity between software (Eadie et al., 2014); all of which deter the adoption of digital technologies in construction projects.

Despite the development of various digital technologies, many scholars studied the factors influencing the adoption of these technologies, significant adoption problems persist in the construction industry (Wang and Li, 2022). In this context, it may be the case that the existing research treats the influencing factors as a whole and lacks attention to the association between these influencing factors. This results in the mechanism of factors that affect the adoption of digital technologies akin to some sort of a "black box". That is, many previous studies have considered the separate effects of influencing factors on the adoption of digital technologies, but ignored the configuration (i.e. combination) effects among multiple factors. In this regard, Woodside (2017) found that a single factor is rarely sufficient for achieving a specific outcome. Instead, the study suggested that the configuration of multiple factors is almost always more important than the impact of a single factor. Indeed, the configuration perspective can be used to comprehensively and thoroughly analyze the complex causal mechanisms of influencing factors formation (Fiss, 2011). Furthermore and by using achievement goal theory and job design frameworks, Moh'd (Moh'd et al., 2021) identified knowledge hiding antecedents through literature analysis, and conducted fuzzy set qualitative comparative analysis on employee data of 10 Chinese medium-sized enterprises through using the configuration method. The study identified four antecedent configurations that lead to knowledge hiding and six configurations that inhibited this behavior. Those configurations provided different approaches and solutions for reducing knowledge hiding behavior among project team members. Conversely, Pittino (Pittino et al., 2017) studied the motivations and personality traits that trigger entrepreneurial actions in three strategic leadership scenarios through literature and expert-based research. Using fuzzy set qualitative comparative analysis of the collected sample of owners/managers of Italian SMEs, 12 configurations of internal and external motivations and personality characteristics conducive to entrepreneurial orientation were determined. The results from the study provided guidance for enterprises to trigger entrepreneurial orientation and improve corporate performance. Hence, as in these two example cases, the configuration perspective has been used in institutional, logical, entrepreneurship, management and other fields, for providing new solutions to many practical problems. However, it has been scarcely used in the technology adoption field.

Analogously, and in recent years, the rapid development of the construction industry has involved an increasing number and diversity of participants, production factors, and requirements, which has led to the promotion of digital technologies based on the identification of a single influencing factor, which can no longer meet the needs of digital transformation in the construction industry (Sun, 2021). As an adoption area for digital transformation in the construction industry, major projects that empower the transformation and upgrading of engineering construction with digital technologies are crucial to achieving lean construction in the engineering construction process. Major projects (also known as megaprojects) refer to major engineering infrastructure projects (Flyvbjerg et al., 2003), which are large-scale public engineering projects delivered to provide support and services for social production, economic development, and improving people's lives. Such projects have a significant impact on the economy, national security, people's lives and social dimensions, science and technology, and the natural environment. As distinct from ordinary projects, major projects have the characteristics of huge investment scale, large engineering complexity, long construction period, high risks for various types of engineering projects, many stakeholders as well as extensive and far-reaching influence. For example, this includes large-scale infrastructure projects, high-speed rail projects, and urban comprehensive pipeline projects.

In addition and in recent years, China's construction industry has led the transformation and upgrade of the traditional construction industry with technological innovation, a number of major construction technologies have achieved breakthroughs, some construction technologies have reached the world's leading level, and various types of engineering projects with the world's top level (e.g. high-speed railways, highways and bridges) have continued to emerge (China T C P S G O T P S R O, 2021). Hence, China's construction industry is deemed a representative case study, since its construction industry has faced and undergone the adoption of many new technologies in a relatively short period of time. Thus, taking some of China's major infrastructure projects as the starting point, the study determines the influencing factors for the adoption of digital technologies in major projects in the construction industry by combining DOI and TOE. The study attempts to explore the antecedent configuration path for the adoption of digital technologies in major projects from a new perspective (i.e. configuration perspective), and provide new solutions for promoting the adoption of digital technologies. The study has the following research questions: (1) What are the antecedent pathways that have a significant impact on the adoption of digital technologies? (2) What are the core or edge characteristics of each antecedent in these paths? Consequently, the solutions to these questions can be viewed as providing the key to opening the previously mentioned 'black box' for the adoption of digital technologies.

Among the six categories of digital technologies included in this study (i.e. BIM, artificial intelligence, blockchain, big data, cloud computing, and Internet of Things), and after expert investigation and literature analysis, it was found that BIM technology and artificial intelligence are most widely used in current large-scale construction projects (Abioye et al., 2021). While other technologies, such as blockchain, big data, cloud computing, and Internet of Things, can be considered as being in a wait-and-see state of development (Bilal et al., 2016; Hamledari and Fischer, 2021b). Therefore, this empirical research study focuses on four major technologies, namely: blockchain, big data, cloud computing, and the Internet of Things.

Regarding the adoption of digital technologies in major projects, this study integrates DOI (diffusion of innovation) and TOE (technology-organization-environment) theories; combines expert surveys based on existing literature; incorporates interoperability and participant collaboration into the influencing factor system; and identifies influencing factors for the adoption of digital technologies in major projects in the construction industry. Also, unlike existing research on influencing factors of the adoption of digital technologies, the study systematically determines the relationship between the antecedent conditions of digital technology adoption from a new perspective (i.e. configuration perspective).

The structure of this article is as follows. Firstly, the theoretical background is introduced, the influencing factors are obtained through literature analysis and expert investigation, and the theoretical framework is constructed. Secondly, according to the literature review findings and maturity scale, the measurement items of each factor questionnaire were established, and the questionnaire collection and reliability and validity tests were carried out. Finally, the necessary conditions and configuration analysis are carried out, the conclusions are drawn, and management implications are provided.

2. Theoretical background

As the adoption of digital technologies requires organization-wide adoption (including adoption in the project delivery network) and since this research focuses on studying the adoption of digital technologies among major projects (and not individuals), an organizational-level adoption theory is deemed suitable for the current research (Ahuja et al., 2016). Two theories are commonly used in innovation diffusion and adoption studies in organizations (Oliveira et al., 2014). They are the DOI theory and the TOE Framework. Other popular theories, such as the technology acceptance model (TAM) (Davis, 1985) (Davis, 1989), the theory of planned behavior (TPB) (Ajzen, 1991), and the unified theory of acceptance and use of technology (UTAUT) (Venkatesh et al., 2003), are not considered in this research because they pertain to an individual's choice (Oliveira et al., 2014).

2.1. Diffusion of innovation (DOI) theory

Rogers' (Rogers et al., 2014) theory on the diffusion of innovation (DOI) is widely used to study various innovation diffusion phenomena through defining innovation diffusion as the process of spreading through a certain period; through a specific channel; and among members of a social group. In the field of information technology (IT), innovation diffusion theory identifies that factors such as the characteristics of technology, the characteristics of potential users, and the organizational context are all important determinants of IT acceptance and use (Lei, 2016). Indeed, DOI theory is widely used in research on the influencing factors of the adoption of digital technologies such as blockchain (Kouhizadeh et al., 2021) and BIM (Chen and Ni, 2019) in the field of engineering construction.

2.2. TOE framework

The theoretical framework of TOE was proposed by Tornatizky & Fleischer (Tornatzky et al., 1990). The framework explores the influencing factors of the application and proliferation of emerging technologies from three levels, namely technology, organization, and the environment (TOE). The TOE framework has received extensive attention from scholars. The technical dimension mainly considers the characteristics of the technology itself. The organizational dimension includes organizational culture and organizational resources (Abed, 2020). The environmental dimension includes factors such as government policy and competitive pressure (Qalati et al., 2021). The TOE framework is widely used in the study of the complexity of major projects (Bosch-Rekveldt et al., 2011).

2.3. Combining DOI and TOE

To improve our understanding of the adoption of innovative new technologies, many researchers have called for approaches that combine more than one theoretical perspective to ensure the context of the study is comprehensive (Wu et al., 2013). Indeed, DOI and TOE have been used extensively in IT adoption studies. In many ways, the TOE perspectives overlap with the innovation characteristics identified by Rogers. Therefore, the value of incorporating the DOI to strengthen the TOE theory is well-recognized (Oliveira and Martins, 2011). The technology level is implicitly the same idea as that of Rogers (Rogers et al., 2014). Moreover, DOI's organizational characteristics include the same measures as TOE's organization level (Hsu et al., 2006). There are also important differences between the two theories. The TOE does not specify the role of individual characteristics (e.g., top management support). Here, the DOI theory suggests the inclusion of top management support in the organization level. Similarly, DOI does not consider the impact of the environmental level. Because of DOI's short comings, the TOE framework helps to provide a more comprehensive perspective for understanding IT adoption by including the technology, organization, and environment level (Zhu et al., 2006). The theories thus meaningfully complement each other (Oliveira and Martins, 2011) (Oliveira et al., 2014).

Many scholars also use DOI and TOE as the theoretical basis for technology adoption research. Oliveira (Oliveira et al., 2014) identified three factors (i.e. relative advantage, complexity and compatibility) using DOI theory in research on the determinants of cloud computing adoption in manufacturing and service industries. The study also identified factors at the technical, organizational and environmental levels, such as technical readiness, high-level support, and competitive pressure under the guidance of the TOE framework. Some scholars have integrated DOI and TOE, and studied technical characteristics such as comparative advantage, complexity and compatibility proposed by DOI theory as technical factors in the TOE framework (Low et al., 2011). However, these studies focus on manufacturing, services and high-tech industries, and do not focus on construction and engineering projects. This research combines DOI and TOE focusing on major projects in the construction industry and undertakes technology adoption research with digital technologies as a whole.

2.4. Theoretical framework

In this study, the "TOE-D Technology Adoption Antecedent Framework" is constructed by combining DOI theory and the TOE framework (see the left side of Fig. 1). First, the DOI theory is integrated into the TOE framework, and the sub-levels at the technical, organizational and environmental levels are determined under the guidance of the theory. Secondly, under the three levels (i.e., technology, organization and environment) and corresponding sub-levels, the antecedent factors of digital technology adoption are obtained. This is achieved through harnessing a literature analysis and expert survey method combined with analysis of the major engineering characteristics of the construction industry. Finally, the "TOE-D Technology Adoption Antecedent Framework" is constructed. The complexity, compatibility and relative advantage in the framework are the technical characteristics proposed by DOI theory; top management support is the role of personal characteristics proposed by DOI theory; and the remaining antecedents are derived under the guidance of TOE framework and major project characteristics. The specific process is as follows.

The diffusion of innovation (DOI) theory divides the characteristics of innovative technologies into five variables, namely complexity, compatibility, observability, relative advantages, and trialability, and asserts that these five characteristics of innovative technologies are the main factors affecting the diffusion of innovative technologies (Rogers et al., 2014). Hence, this study uses innovation diffusion theory as a guide to classify the technical characteristics of influencing factors at the technical level.

The TOE model, on the other hand, argues that the needs of an organization have a significant role in the adoption of innovation-related decisions. However, even if an organization has a strong willingness to adopt, that innovation may not necessarily be well absorbed by the organization (Fichman and Kemerer, 1997). This is because the adoption of new IT innovations by organizations needs to be based on organizational readiness (Wang et al., 2010). Hence, assuming an organization acts rationally, the organization must measure its organizational readiness such as knowledge and resources before committing to the adoption of innovation practices (Abed, 2020). Therefore, the influencing factors at the organizational level in this study are divided into 'organizational needs' and 'organizational readiness.'

Finally, actors are constrained by their environment (i.e. context), and therefore completely independent rational decision-making does not exist (Teng et al., 2017). In TOE theory, the environmental level pays more attention to the influence of external factors on companies. Hence, this study divides the environment level into two areas: 'external norms' and 'competitive pressure'.

According to the lens of the three levels (i.e. technology, organization, and the environment) and corresponding sublevels detailed above, the study performed a literature review on digital technologies adoption in construction. The scope of the literature review included articles from the Web of Science and the China National Knowledge Infrastructure (CNKI) databases published after 2010. The search keywords included: "major projects", "digital technologies", "technology adoption", and "innovative application". More than 50 publications most closely related to digital technology adoption were sifted and sorted out. Combined with the survey data of experts, 11 influencing factors for the adoption of digital technologies in major projects were identified.

At the technical level, Chong (Chong et al., 2009) identified that trialability and observability are not widely used in IT innovation studies. Whereas Tornatzky and Klein (1982) believe that complexity, compatibility, and relative advantages are closely related to technology diffusion and are strong, but observability, trialability, and technology diffusion are not closely related. Therefore, referring to Gangwar (2018), this study only considers the three technical characteristics of complexity, compatibility, and relative advantages in innovation

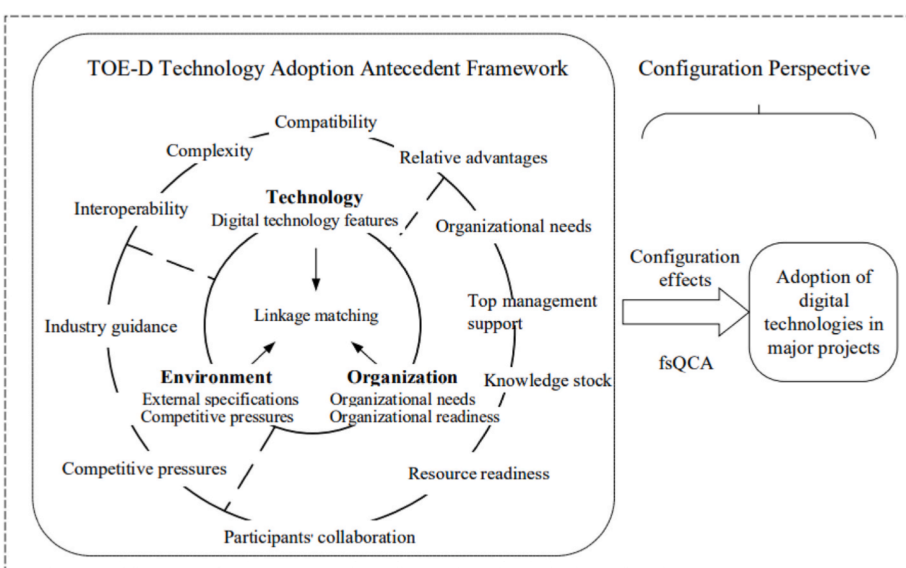

Fig. 1. Theoretical framework adopted in study.

diffusion theory. In addition, expert surveys point out that interoperability between technical data and software is also one of the important obstacles to the current technology adoption. The research of many scholars also proves the importance of technical interoperability (You and Wu, 2019) (Jin et al., 2017). Hence, the technical level included four digital technologies characteristics, namely: complexity, interoperability, compatibility, and relative advantages.

Among the factors at the organizational level, top management support appears most frequently, and many scholars such as Gangwar (2018), Lai (Lai et al., 2018), and Ifinedo (2011) demonstrated the important role of top management support in technology adoption. Secondly, the readiness for organizational knowledge and resources is also an important influencing factor in the research of Chaveesuk (Chaveesuk et al., 2020), Abed (2020), and Lai (Lai et al., 2018). Scholars such as Tallon (Tallon et al., 2019) highlight the important impact of organizational needs on technology adoption. In addition, experts noted that major projects are characterized by a large number of stakeholders, and the level of collaboration among participants may have a crucial impact on the adoption of digital technologies. Therefore, the research of Li and Liu (2019), and Andersson (Andersson et al., 2016) can be considered to include the factor of participant collaboration. In summary, the organizational level ultimately includes five factors, namely: organizational needs, top management support, knowledge stock, resource readiness, and participant collaboration.

Regarding the environmental level, the research of Bilal (Bilal et al., 2016), Alshamaila (Alshamaila et al., 2013), and Barlish and Sullivan (2012) are acknowledged, including industry guidance and competitive pressures (see Appendix I for further details and sources). In summary, the "TOE-D Technology Adoption Antecedent Framework" was constructed according to the configuration perspective, and the theoretical framework developed in this study is shown in Fig. 1.

The "TOE-D Technology Adoption Antecedent Framework" constructed in this study integrates DOI theory and TOE framework, which complement each other and provide a more comprehensive perspective for the identification of technology adoption antecedents. At the technical level, through expert investigation, interoperability is added on the basis of existing literature, thereby highlighting the impact of data and software interoperability on technology adoption, and providing systematic guidance for technological breakthroughs. At the organizational level, the increase in participant collaboration is based on the characteristics of many stakeholders of major projects. However, there are upstream and downstream enterprises and production supply chains in various industries, and the addition of the antecedent of "participant collaboration" helps to improve the collaborative relationship between organizations and effectively help break through the barriers to technology adoption at the organizational level. At the environmental level, external norms are further focused on industry guidance, and on the basis of proposing supportive policies. In this regard, the establishment of relevant standards, norms and guidelines is emphasized to provide the most practical and direct guidance for the adoption of digital technologies. In summary, the framework contains a total of 11 antecedent factors at the technical, organizational and environmental levels. Compared with the antecedent factors identified in previous studies, the framework provides a more comprehensive and efficient guidance on technology adoption on the basis of rationality and thereby helps to break through the barriers of technology adoption.

3. Research methods

3.1. Fuzzy set qualitative comparative analysis

In this study, fuzzy set qualitative comparative analysis (fs QCA) is used to analyze the configuration of digitization technology adoption for major project based on antecedent inputs. We used the fsQCA3.0 software to perform all calculations. The reasons behind the use of fs QCA are two: (1) Most of the existing studies examine the separate effects of influencing factors on technology adoption in isolation, using traditional regression analysis to examine the "independent net effect" of a single variable on the outcome variable, while ignoring the "configuration effect" of multiple antecedent conditions on the outcome in the interdependence and interaction (Ragin, 2009). While a single factor is rarely a sufficient condition for producing results. The fs QCA method helps to analyze the driving mechanism of multiple factors in the adoption of major engineering digital technologies from a configuration perspective. (2) The path to improve the adoption of digital technologies in major projects is often not unique. Major project participants frequently choose to interact with different combinations of technologies according to specific conditions to achieve their purposes. In this regard, fs QCA complements traditional symmetry methods by accommodating data asymmetries. This means fs QCA can identify potential interdependencies between antecedent conditions, and reveal multiple equivalent pathways to achieve the same outcome under specific conditions.

3.2. Measurements

Once influencing factors have been identified and the fs QCA method has been introduced, a questionnaire survey was designed. This questionnaire aimed to answer the research questions: (1) What are the antecedent paths that have a significant impact on the adoption of digital technologies? (2) What are the core or edge characteristics of each antecedent in these paths? The questionnaire was designed to ascertain the current situation of each influencing factor and the current application of digital technologies in major projects. The adoption of technologies is not a simple adoption of digital technology, and the in-depth application of digital technology in major projects should be realized, such as the adoption of blockchain technology should include the application of smart contracts, secure payment, or quality traceability in major projects. The adoption of big data technology should enable in-depth analysis and mining of complex and large amounts of information and data in engineering management practices. Whereas the adoption of the Internet of Things should enable intelligent identification, operation, or management functions. The adoption of cloud computing should include the application of a cloud computing platforms to realize the integration and allocation of existing resources such as construction, design, supervision, quality control, and material supply.

All questionnaire dimensions, question items, and their corresponding scales were based on existing literature sources to ensure their validity. As a result, the questionnaire included 14 question items at the technical level, 12 question items at the organizational level, and 4 items at the environment level. Finally, the adoption of digital technologies in major projects (ADTMP) included two questions. All question items and sources for all variables are summarized in Table 1.

3.3. Data collection

The data collection process involved the following steps. Firstly, as described earlier, both the questionnaire structure and scales were preliminarily determined based on a literature review. Secondly, the questionnaire structure system was reviewed and revised by experts. Thirdly, an initial questionnaire was created and a pre-survey was carried out. A small number of industry experts were invited to conduct a questionnaire pilot test and, according to their feedback, the questionnaire was partially modified. Namely, ambiguous questions were refined and some questions with a high degree of overlap were removed. This way, the final questionnaire was obtained for use in the main part of the research project.

The questionnaire consisted of two parts, the first part looked at the basic profile of the respondents, and the second part investigated the current status of digital technology adoption factors and outcomes. The data recovered from the questionnaire were sorted out and statistically

Table 1
Questionnaire questions and sources.

Influencing factors	Items	Source
Complexity (CE)	CE1: Major project participants found the use of digital technologies software complex. CE2: Major project participants see the adoption of digital technologies as a complex process. CE3: To adopt digital technologies, major project participants do not need to spend significant time and cost.	CE1 and CE2 are adapted from Grover (Grover, 1993) CE3 is adapted from Ifinedo (Ifinedo, 2011)
Interoperability (IA)	IA1: The data formats and standards of digital technologies are compatible with existing software and hardware. IA2: The data generated by the digitization technology-related software can be easily transmitted to and from other software.	IA1 is adapted from Ramamurthy (Ramamurthy et al., 1999) IA2 is adapted from Grandon and Pearson (Grandon and Pearson, 2004)
Compatibility (CA)	CA1: The adoption of digital technologies is consistent with the development strategies and values of major project parties. CA2: The adoption of digital technologies is compatible with the existing business processes of major project parties.	Adapted from Grover (Grover, 1993) and Ramamurthy et al. (Ramamurthy et al., 1999)
Relative advantages (RA)	RA1: Digital technologies allow major project participants to focus on their core business. RA2: Digital technologies allow major project participants to avoid risks. RA3: Digital technologies can help major project participants improve their skills and management capabilities. RA4: Digital technologies can help major project participants improve performance. RA5: Implementing digital technologies can outperform competitors in the industry.	RA1 and RA4 are adapted from Grandon and Pearson (Grandon and Pearson, 2004) RA2 and RA5 are adapted from Lin (Lin, 2006) RA3 is adapted from Ifinedo (Ifinedo, 2011)
Organizational needs (ON)	ON1: Major project participants have internal needs to implement digital technologies. ON2: The need for digital technologies is urgently compared to other needs. ON3: The demand for digital technologies is a value-added link in the value chain of major project participants.	Adapted from Ifinedo (Ifinedo, 2011) and She (She et al., 2010)
Top management support (TMS)	TMS1 : Top management is interested in the adoption of digital technologies. TMS2 : Top management provides support in terms of people, talents, and materials. TMS3 : Top management is actively involved in the adoption process of digital technologies. TMS4 : Top management is willing to take the risk of implementing digital technologies.	TMS1 and TMS4 are adapted from Soliman and Janz (Soliman and Janz, 2004) TMS2 is adapted from Lin (Lin, 2006) as well as Soliman and Janz (Soliman and Janz, 2004) TMS3 adapted from Lin (Lin, 2006)
Knowledge stock (KS)	KS1: Major project participants have extensive experience in digital technologies project management. KS2: Major project participants have implemented similar service outsourcing operations. KS3: Among the major project participants there are experts in digital technologies. KS4: Major project participants are well aware of how digital technologies are being implemented in other companies in the industry. KS5: Major project participants can accurately predict the risks and benefits of implementing digital technologies.	KS1and KS2 are adapted from Alshamaila (Alshamaila et al., 2013) KS3 is adapted from (Lin, 2006) KS4 and KS5 are adapted from Ifinedo (Ifinedo, 2011)
Resource readiness (RR)	RR1: Among the major project participants there is a surplus of human resources to implement digital technologies. RR2: Among the major project participants there are the financial resources needed to implement digital technologies.	Adapted from Grandon and Pearson (Grandon and Pearson, 2004)
Participants' collaboration (PC)	PC1: Major project participants have adopted digital technologies to a similar extent. PC2: The participants in major projects have a good level of collaboration in the adoption of digital technologies.	Adapted from Lin (Lin, 2006)
Industry guidance (IG)	IG1: China's construction industry has formulated a standard contract for the adoption of digital technologies. IG2: China's construction industry has formulated sufficiently good standards and specifications for the adoption of digital technologies.	Adapted from She (She et al., 2010)
Competitive pressures (CP)	CP1: Competitors are embracing digital technologies. CP2: Trading partners have adopted digital technologies.	Adapted from Wu (Wu et al., 2003)
Adoption of digital technologies in major projects (ADTMP)	ADTMP1: The participants in major projects have already applied digital technologies in most of the major projects they have	Adapted from Ifinedo (Ifinedo, 2011)

(continued on next page)

Table 1 (*continued*)

Influencing factors	Items	Source
	been involved in.ADTMP2: The participants in major projects are willing to use digital technologies for project management.	

analyzed with SPSS. The reliability and validity of the questionnaire were also tested. All questions were scored on a 5-point Likert scale, which clearly distinguished the bias and degree of respondents' selection while ensuring the simplicity of the questionnaire and not causing fatigue among the respondents. The survey period lasted from the end of May 2022 to August 2022. The selection criteria for major projects were as follows: (1) they had to be carried out mainly in the past five years; (2) data of multiple stakeholders could be obtained; (3) there was diversity of project scopes (the final list of major projects involved roads, railways, bridges, etc.); (4) the projects had a diverse location (i.e. were located in different provinces or regions in China as much as possible). Under these premises, the questionnaire was distributed among personnel participating in the major projects. Basic information of the representative major projects selected is shown in Appendix II.

After selecting major projects, the internal personnel of each participant in the major project were the target of the questionnaire, and some participants in major projects, such as the Jizheng high-speed railway and the Xi'an urban underground comprehensive pipe gallery, were investigated offline. The personnel from relevant departments such as the Science and Technology Research and Development Center and the Digital Technology Application Center were invited to fill in the questionnaire. We also contacted the head of the relevant enterprise departments online by phone, email, etc., and invite them to forward and fill out the questionnaire within the department. In the end, a total of 217 questionnaires were distributed, 181 questionnaires were recovered, and 155 valid questionnaires were finally obtained through questionnaire screening. Questionnaire screening was performed by removing questionnaires: (1) questionnaires that had been answered in a too-short or too-long time; (2) those with a high repetition rate and/or obvious regularity; (3) those with less than 95% of the answers; (4) and questionnaires that lacked important information and/or had important inconsistencies. As mentioned earlier, in the end, 155 valid questionnaires were obtained, thereby giving an effective recovery rate of 71.43%. The nature of the sample includes developers, design units, construction enterprises, supervision units and operating units. 73.55% of the respondents have a good understanding of digital technology, thereby indicating that the investigators have a certain understanding of digital technology, which ensures the validity of the questionnaire data. The sample distribution and demographic profile are shown in Appendix III. The preliminary statistics of the final questionnaires show that the distribution of the nature of the sample, experience (number of years working), educational background, level or position, and the degree of understanding of digital technologies were all relatively balanced.

3.4. Constructs reliability and validity measures

SPSS 26.0 was used to test the sample data. Reliability and validity analysis results are shown in Appendix IV. Cronbach's α coefficient of each condition remained above 0.700, thereby indicating that each condition had high stability and that the scales had good reliability. The KMO value of the scale was 0.918, whereas the Bartlett spherical test results were acceptable. All this analysis indicated that the study met the conditions for factor analysis.

Additionally, the scale design referred to existing research and the content validity was deemed good. The standardized load coefficients of each condition remained between 0.67 and 0.77, while the CR values were higher than 0.700, and the mean-variance extraction amount (AVE) was always higher than 0.500. All this indicates that the convergence validity of the scale was acceptable.

4. Data analysis

4.1. Analysis of the necessary conditions

According to the requirements of fuzzy set qualitative comparative analysis (fs QCA), the antecedent conditions and results (i.e. outcomes) need to be calibrated first. In this study, after averaging each continuous variable, the data was calibrated according to the standards proposed by (Ragin, 2021) for 5% (i.e. completely non-affiliated), 50% (i.e. intersection), and 95% (i.e. fully subordinate). Further details on the calibration values of the antecedent conditions and outcomes are shown in Appendix V.

After data calibration, the necessary conditions analysis of single antecedent conditions (i.e. each influencing factor) was carried out by fsQCA3.0. The results of this analysis are shown in Table 2. Since the consistency value of each antecedent condition is lower than 0.9, this means no single isolated influencing factor can be independently deemed a necessary condition for the low level of the adoption of digital technologies. Hence, a configuration (i.e. combination) analysis of multiple antecedent conditions is required.

4.2. Configuration analysis

fsQCA3.0 software was used to analyze the configuration (i.e. combination of influencing factors) promoting a higher adoption of digital technologies in major projects. Firstly, the truth table is constructed, and combinations of antecedent conditions for the adoption of digital technologies in major projects are sorted out according to the collected data. Then, set the acceptable case frequency to filter combinations in the truth table, refer to the practice of Ragin (2009), and set the case frequency value to 1.5% of the original number of cases, the total number of cases in this paper is 155, and 1.5% is 2, and based on this, the logical condition combination with the sample number less than 2 is deleted. Finally, the retained combination of logical conditions is re-encoded by referring to the practice of Fiss (2011), recoding the retained combination of logical conditions according to the standard of the original consistency threshold of 0.800 and the PRI (Proportional Reduction in Inconsistency) consistency threshold of 0.70, and when the original consistency and PRI consistency threshold are met, the result of the corresponding logical condition combination is 1, otherwise, the result is 0. After the truth table is constructed and recoded, the Quine-McCluskey module included in the fsQCA3.0 software is used to analyze antecedent configurations of the adoption of digital technologies in major projects. As a result, six potentially explanatory configurations were obtained. These configurations were named C1 to C6, and the results are shown in Table 3. It is summarized into three driving types: "Needs-Resource-Collaboration" (NRC type)(C1, C2, C3, C4), "Resource" under high competitive pressure(R–HCP type) (C5), and "Resource" under low competitive pressure (R-LCP type)(C6). The schematic diagram of the configuration type is shown in Fig. 2. Before the arrow are the facilitating conditions in the configuration (due to the presence or absence of these antecedents), and after the arrows are the barrier conditions. Large circles represent core conditions and small circles represent edge conditions.

5. Results

In this study, the "TOE-D Technology Adoption Antecedent Framework" is constructed by combining DOI and TOE theory, and the configuration of antecedents is analyzed from the perspective of configuration. The results obtained are as follows.

Table 2
Analysis of the necessity of the antecedents.

Antecedent conditions	Consistency	Coverage	Antecedent conditions	Consistency	Coverage
Complexity	0.828	0.073	~ Complexity	0.675	0.686
Interoperability	0.854	0.075	~ Interoperability	0.666	0.713
Compatibility	0.870	0.077	~ Compatibility	0.645	0.656
Relative advantages	0.877	0.077	~ Relative advantages	0.709	0.785
Organizational needs	0.897	0.078	~ Organizational needs	0.646	0.726
Top management support	0.824	0.073	~Top management support	0.631	0.706
Knowledge stock	0.856	0.075	~ Knowledge stock	0.688	0.702
Resource readiness	0.835	0.073	~ Resource readiness	0.671	0.720
Participants' collaboration	0.800	0.071	~ Participants' collaboration	0.713	0.670
Industry guidance	0.889	0.078	~ Industry Guidance	0.617	0.658
Competitive pressures	0.846	0.075	~ Competitive pressures	0.714	0.687

Note: "~" stands for logical not.

Table 3
Antecedent configurations of adoption of digital technologies in major construction projects..

Antecedent conditions	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**
Complexity (CE)	●	●	●	●	●	⊗
Interoperability (IA)	●	●	⨂	●	●	⨂
Compatibility (CA)	•	•	⊗	⊗	•	•
Relative advantages (RA)	●	⊗	●	•	⊗	●
Organizational needs (ON)	●	●	●	●	•	⊗
Top management support (TMS)	•	⨂	•	•	•	⨂
Knowledge stock (KS)	•	⊗	⊗	•	•	⊗
Resource readiness (RR)	●	●	●	●	●	●
Participants' collaboration (PC)	●	●	●	●	⊗	⊗
Industry guidance (IG)	•	⨂	•	•	•	⨂
Competitive pressures (CP)		●	●	●	●	⨂
Consistency	0.994	0.986	0.947	0.953	0.956	0.983
Coverage	0.507	0.239	0.235	0.240	0.245	0.032
Unique coverage	0.056	0.033	0.030	0.024	0.021	0.003
Overall consistency			0.994			
Overall coverage			0.918			

Note: ● represents the occurrence of the core condition; • represents the appearance of the edge condition; ⨂ represents that the core condition does not appear; ⊗ represents that the edge condition does not appear; the space represents that the condition does not matter.

(1) The "TOE-D Technology Adoption Antecedent Framework" includes three levels: technology, organization, and environment. The technical level contains the characteristics of digital technology; the organizational level includes organizational needs and organizational readiness; and the environmental level contains external norms and competitive pressure. the framework uses these levels and sub-levels as a guide to carry out literature analysis to identify the antecedents of the adoption of digital technologies for major projects in the construction industry. Finally, the technical level contains four antecedents of complexity, compatibility, interoperability, and relative advantage. The organizational level includes five antecedents, namely: organizational needs, top management support, knowledge stock, resource readiness, and participant collaboration. The environmental dimension includes two antecedent factors: industry guidance and competitive pressure.

(2) In this study, the preceding factor configuration path was analyzed by the fs QCA method from the perspective of configuration, and six configurations adopted by major engineering digital technologies were obtained. According to the core conditions of the configuration, the six configurations can be summarized into three driving types: "Needs-Resource-

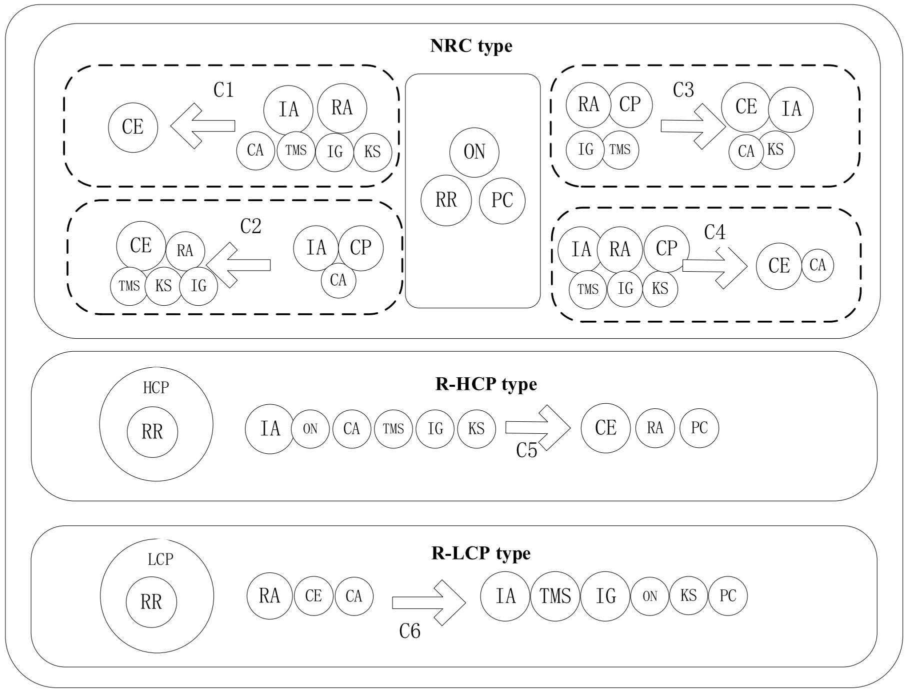

Fig. 2. Schematic diagram of the configuration type.

Collaboration" (NRC type) (C1, C2, C3, C4), "Resource" under high competitive pressure (R–HCP type) (C5), and "Resource" under low competitive pressure (R-LCP type) (C6).

(3) After obtaining the six configuration paths adopted by major engineering digital technologies, the configurations are compared horizontally to obtain the core edge characteristics of each antecedent in the path. Among them, complexity is often the core problem of digital technology adoption. Resource readiness is defined in each configuration as a core element that facilitates technology adoption. The interoperability of technologies and the existence of competitive pressures in the external environment are the core elements to improve the status quo of technology adoption, and their absence is also the core obstacle to technology adoption. The existence of the two factors of senior management support and industry guidance is mostly auxiliary factors to promote technology adoption, but their lack is mostly an important issue of technology adoption. The existence of three factors that relative advantage, organizational needs, and participant collaboration is the core factor of some configurations, and their lack does not constitute the core problem of technology adoption. Technical compatibility and organizational knowledge stock are mostly edge conditions in the configuration, and their existence can be used as auxiliary tools to improve the application level of digital technology, and their lack does not become a core obstacle.

6. Discussion

6.1. *Discussion of the "TOE-D Technology Adoption Antecedent Framework"*

The "TOE-D Technology Adoption Antecedent Framework" including three levels of technology, organization, and environment, and the technical level includes four technical characteristics of complexity, compatibility, interoperability, and comparative advantage, among which complexity, compatibility, and comparative advantage are extracted from the innovative technical characteristics proposed by innovation diffusion theory (DOI) by reference to the research of Gangwar (2018) and Oliveira (Oliveira et al., 2014). Interoperability is rarely involved in the influencing factors of technology adoption identified in the current research, but the importance of interoperability is reflected in the research of You and Wu (2019) and Jin et al. (2017), where the difficulty of data sharing between business information systems and weak data interoperability will lead to managers unable to obtain real-time data related to construction projects, which in turn will lead to the inability of senior management to make effective decisions. The survey by Jin et al. (2017) found that internal and external collaboration and interoperability between multiple BIM software tools are priorities for BIM investments. Therefore, this study builds on existing research to add interoperability to the antecedent framework.

The organizational level contains two sub-levels: organizational requirements and organizational readiness. This is consistent with the research of Kim and Garrison (2010), which combined organizational needs and organizational readiness factors (including financial status and technical knowledge) with the project implementation process of enterprises to construct a research model of technology adoption behavior. Organizational readiness includes four antecedents: senior management support, knowledge stock, resource readiness, and participant collaboration. Among them, top management supports the addition of DOI theory, and its significant impact on technology adoption has been confirmed in the research of Gangwar (2018) Lai et al. (2018) and Ifinedo (2011). Knowledge stock and resource readiness have also been identified by scholars such as Chaveesuk et al. (2020), Abed (2020), and Lai et al. (2018) as influencing factors for technology adoption. While collaboration is rarely involved in current research on the influencing factors of technology adoption, Jin et al. (2017) points out that internal and external collaboration is a priority for BIM investment. Li and Liu (2019) pointed out the important role of enterprise collaboration in innovation and believed that technology adoption should adapt to the needs of enterprise collaborative production, promote the collaborative development of enterprises, and a low level of collaboration will lead to additional innovation costs. Due to a large number of participants in major projects, this study incorporates the collaboration of participants into the framework of technology adoption.

The environmental dimension includes external norms and competitive pressures, of which external norms mainly contain industry guidance. The role of industry guidance and competitive pressure has been widely recognized in the IT adoption literature (Gangwar, 2018) (Alshamaila et al., 2013). In summary, this study combines DOI and TOE theories, constructs antecedent framework levels and sub-levels under the guidance of theory, and then adds interoperability and participant collaboration based on existing literature through literature analysis and expert survey, and finally identifies 11 antecedent factors.

6.2. Discussion of configuration results

The configuration paths identified in this study include three driving types: "Needs-Resource-Collaboration" (NRC type), "Resource" under high competitive pressure (R–HCP type), and "Resource" under low competitive pressure (R-LCP type):

"Needs-Resource-Collaboration" (NRC type) (C1、C2、C3、C4): The antecedent condition for configuration C1 is CE*IA*CA *RA*ON*TMS*KS*RR*PC*IG. This configuration has complexity, interoperability, relative advantage, organizational needs, resource readiness, and collaboration by participants as core conditions; and compatibility, top management support, knowledge stock, and industry guidance as auxiliary conditions. This path shows that when digital technologies are characterized by strong compatibility, especially strong interoperability and obvious relative advantages, but high complexity, the focus is on clarifying organizational needs and ensuring sufficient manpower, material, and information resources. Moreover, the focus also remains on improving the level of collaboration among participants in major projects, and this is supplemented by industry guidance, top management support, and knowledge stock.

A possible interpretation of this finding is that digital technologies have become complex integrated systems, and the development of these complex technologies requires the integration of multiple technical and organizational resources. Indeed, Tornatzky (Tornatzky et al., 1990) identified that recognizing the advantages of leading enterprises with a strong association and driving role, using leading enterprises to drive the associated enterprises to clarify organizational needs, improve the ability to integrate innovation resources, and improve the level of professional cooperation between enterprises. This is crucial to the innovation of complex technologies. Overall, these findings highlight the importance of three factors in overcoming technical complexity: organizational needs, resource readiness, and participants' collaboration.

The antecedent condition for configuration C2 is CE*IA*CA *∼RA*ON*∼TMS*∼KS*RR*PC*∼IG*CP. This configuration has complexity, interoperability, organizational needs, non-top management support, resource readiness, participants' collaboration, non-industry guidance, and competitive pressures as the core conditions; and compatibility, non-relative advantage, non-knowledge stock, and auxiliary conditions. This path shows that when digital technologies are characterized by strong compatibility and especially strong interoperability, but high complexity, there are problems such as insufficient relative advantages, insufficient knowledge stock of participants, and imperfect industry guidance, the key to breaking the barriers for the adoption of digital technologies in major projects is to have clear organizational needs, high organizational resource readiness, high collaboration level of participants, and appropriate external competitive pressure.

This means that, when the technology is complex and the relative advantage is insufficient, competitive pressures have become the key to the adoption of digital technologies when faced with the problem of a low level of top management support, insufficient organizational knowledge stock, and imperfect industry guidance of digital technologies. Indeed, competitive threats from the same industry are the source of motivation for the innovation activities of organizations (An Vinh Nguyen et al., 2020). Under constant pressure from industry and competitors, organizations often need to exploit potential strengths by adopting digital technologies, i.e. competitive pressures force organizations to consider adopting new technologies (Hossain et al., 2017). Therefore, the competitive pressure of appropriate intensity promotes the coordinated development of digital technologies adoptions among the various entities of major projects.

Configuration C3: The antecedent condition is CE*∼IA*∼CA *RA*ON*TMS*∼KS*RR*PC*IG*CP. This configuration has complexity, non-interoperability, relative advantage, organizational needs, resource readiness, participants' collaboration, and competitive pressures as the core conditions; and non-compatibility, top management support, non-knowledge stock, and industry guidance as auxiliary conditions.

Knowledge is the driving force for team innovation. Resources and relationships (including some environmental factors) are also important conditions for innovation (Li and Liu, 2019). If the technology is complex, the interoperability is poor and the organizational knowledge stock is insufficient, it is necessary to rely on the organizational needs and competitive pressure to promote innovation adoptions with the support of the top management. This means it is necessary to support the company to obtain technical knowledge through other channels through organizational resources and collaboration. In this regard, software interoperability standards issued by the industry's authorities and collaborative platforms can solve the problem of poor technical digital technologies interoperability to a certain extent (Blind et al., 2017).

Configuration C4: The antecedent condition is CE*IA*∼CA *RA*ON*TMS*KS*RR*PC*IG*CP. This configuration has complexity, interoperability, organizational needs, resource readiness, participants' collaboration, and competitive pressures as the core conditions; and non-compatibility, relative advantage, top management support, organizational knowledge stock, and industry guidance as marginal conditions. This path shows that when digital technology has poor compatibility and is highly complex, yet it has relative advantages and strong interoperability, it can overcome the disadvantages of the technology itself, and improve the adoption of digital technologies in major projects. This is also supported by improving organizational needs, resource readiness, participants' collaboration, and competitive pressure, combined with top management support and high organizational knowledge stock and industry guidance.

The essence of technological innovation is the creation of knowledge, and the development of innovative activities in the organization depends on its knowledge base (Andersson et al., 2016). Therefore, when a digital technology faces multiple problems that hinder its adoption (e.g. high complexity, poor compatibility, poor observability), the organizational knowledge stock has also become a supporting condition for the application of digital technologies by major project participants together with top management support and industry guidance. Still, organizational needs, resource readiness, participants' collaboration, and competitive pressure remain key factors.

"Resource" under high competitive pressure(R–HCP type) (C5): The antecedent condition is CE*IA*CA *∼RA*ON*TMS*KS*RR*∼PC*IG*CP. This configuration has complexity, interoperability, resource readiness, and competitive pressure as the core conditions; and compatibility, non-relative advantages, organizational needs, top management support, knowledge stock, non-participants' collaboration, and industry guidance as auxiliary conditions. This path shows that when digital technologies are characterized by strong compatibility and especially strong interoperability, but high complexity, having insufficient relative advantages, it is necessary to improve the readiness of organizational resources as the core, adopt competitive pressure as the driving force, and supplement the conditions by clear organizational needs, top management support, high knowledge stock, and perfect industry guidance. This configuration overcomes the problem of a low level of collaboration among major project participants and the disadvantages of the technology itself and promotes the adoption of digital technologies.

If technology compatibility is good, sufficient resources, coupled with organizational needs, high-level support, knowledge, and industry guidance, driven by competitive pressures, can still compensate for the lack of technical complexity, comparative advantages, and collaboration between participants. Although compatibility is an edge condition in this configuration, good compatibility means that the adoption of technology matches the company's existing business processes, infrastructure, supply channels, company culture, and values, which to some extent reduces the perception of technical complexity, and with the help of industry guidance, a compatible technology will make the technology adoption process smoother, thereby reducing the need to get help from other participants (Chen and Ni, 2019).

"Resource" under low competitive pressure (R-LCP type) (C6): The antecedent condition is ~CE*~IA*CA *RA*~ON*~TMS*~KS* RR*~PC*~IG*~CP. This configuration has non-interoperability, relative advantages, non-top management support, resource readiness, non-industry guidance, and non-competitive pressures as core conditions; and non-complexity, compatibility, observability, non-organizational needs, non-knowledge stock and non-participants' collaboration as auxiliary conditions.

It can be observed that a rare situation is if the technical interoperability is weak and many problems exist, such as unclear organizational needs, low level of top management support, insufficient knowledge stock, low level of participants' collaboration, imperfect industry guidance, and low competitive pressure. Due to the advantages of the technology itself, the resource readiness within the organization as the material basis for organizational technological innovation can overcome many problems at the organizational and environmental levels to a certain extent (Li and Liu, 2019).

6.3. Discussion of configuration horizontal comparison

Comparing the above six configurations horizontally, it is found that.

(1) Complexity exists as a core problem in the adoption of digital technologies. This is consistent with the findings of Gangwar (2018), Oliveira (Oliveira et al., 2014) that complexity is a barrier to the adoption of digital technologies. Complexity can be related to the perception of change, which can lead to discomfort and frustration that hinders decisions about the adoption of digital technologies by major projects participants.

(2) Resource readiness is the presence of core elements in each configuration to facilitate technology adoption. Resource readiness includes the readiness of human, material, financial and other resources. Li and Liu (2019) pointed out that resources are the material basis of innovation, and resource readiness, as a material guarantee for technology adoption, plays an essential role in digital technologies adoption.

(3) The existence of interoperability and competitive pressures are the core elements to improve technologies adoption, and their lack is also the core obstacle to technologies adoption. Technical interoperability includes the interconnection between data and software, and good interoperability will greatly accelerate the data transmission rate, simplify the adoption process of digital technologies, and reduce the complexity of the perception of digital technologies by major project participants. Poor interoperability due to software interoperability and data transmission has seriously hindered the adoption process of digital technologies and become the core obstacle to technology adoption.

The findings of competitive pressures are consistent with the findings of Low (Low et al., 2011) and Ifinedo (2011), which show that competitive pressures have a positive impact on the adoption of digital technologies, Low (Low et al., 2011) points out that competitive pressures drive companies to adopt digital technologies faster, and that more intense competition often pushes organizations to shift from old technologies to digital technologies to gain competitive advantage by adopting a more holistic approach to innovation. The lack of competitive pressures will lead to the lack of external driving force in the process of digital technologies adoption by major projects participants, which is not conducive to enterprises' exploration of the potential advantages of digital technologies and their competitiveness.

(4) The presence of top management support and industry guidance, are mostly auxiliary factors to promote technologies adoption, but their lack is mostly an important problem of technologies adoption. Gangwar (2018) identified that top management support is important in explaining the adoption of digital technologies. The study's evidence suggests that top executives can influence the adoption of digital technologies by showing support by investing in financial and organizational resources and participating in the process. The existence of top management support and industry guidance may play an auxiliary role because top management influences other factors to support the adoption of digital technologies by investing organizational resources, developing IT capabilities, resolving conflicts, improving communication, persuading employees, etc. Whereas industry guidance provides relevant standards for digital technologies adoption, facilitates its resource integration, knowledge acquisition, and ultimately overcomes implementation barriers. If these two factors are absent, the lack of support and guidance for digital technologies adoption will seriously affect digital technologies adoption decisions and hinder the process of digital technologies adoption.

(5) The existence of three factors, including relative advantages, organizational needs, and participants' collaboration, is the core factor of some configurations, and its lack does not constitute the core problem of technology adoption. Relative advantages include improving the quality of business operations, performing tasks faster, increasing productivity, and providing new business opportunities. Organizational needs describe the degree of demand that an organization needs for digital technologies adoption. The existence of these two factors will encourage major project participants to actively adopt digital technologies (Oliveira et al., 2014). participants collaboration plays a central role in some configurations because it provides an effective way for major project participants to share information and exchange knowledge between organizations (Gangwar, 2018). The core issues that hinder the adoption of digital technologies are often the immediate problems that prevent technologies adoption.

(6) Technical compatibility and organizational knowledge stock are mostly edge conditions in the configuration, and their existence can be used as auxiliary tools to improve the adoption of digital technologies, and their lack does not become a core obstacle. The adoption of digital technologies needs to be compatible with an organization's policies, IT development environment, and business needs (Lin and Chen, 2012). Organizations tend to have a positive attitude toward technological innovation and agree on it when there is a good fit between it and the people, processes, and practices across the organization. Knowledge as a driver of team innovation also promotes technologies adoption. In addition, since business processes can be adjusted and knowledge acquisition can be achieved through resources and participants' collaboration, compatibility and lack of knowledge stock are not significant barriers to technologies adoption.

7. Conclusions

This empirical study combined with DOI and TOE theory, constructed the "TOE-D Technology Adoption Antecedent Framework" through literature analysis, including 11 antecedents of technology adoption. Furthermore, through literature analysis, a survey of experts, and fs QCA, six configurations (i.e. combinations) of influencing factors that enhance the adoption of digital technologies in major projects are identified and categorized into three types, namely: "Needs-Resource-Collaboration" (NRC type) (C1, C2, C3, C4); "Resource" under high competitive pressure (R–HCP type) (C5); and “Resource” under low competitive pressure (R-LCP type) (C6).

On this basis, the following practitioner implications are identified.

(1) The high organizational resource readiness in each configuration is the core element, and organizational resource readiness is the focus of improving the adoption of digital technologies in major projects. Hence, practitioners involved in delivering major projects should focus on improving resource readiness in their organizations. Senior management involved in the delivery of the major project should promote the attraction and training of talents, and promote the involvement of multidisciplinary teams. Furthermore, they should strengthen the management of economic funds for the adoption of digital technologies. Senior management should also expand multi-channel fund-raising schemes to limit the risks of failed digital technologies, while also providing adequate support for the upgrade of technical equipment in the organizations.

(2) The context of technology interoperability and competitive pressures in the external environment are key factors in the adoption of digital technologies for major projects. The government and industrial authorities should promote cooperation and exchanges between engineering companies from the construction industry. Both should also strive to create a healthy competitive market environment that takes into account companies with different resource levels and development strategies. For industry-leading state-owned construction enterprises, the government should carry out pilot applications of relevant digital technologies, and vigorously support research and expansion of those technologies. For industrial companies with slow technological development, the government and industry must increase the pressure to increase their motivation to gradually explore relatively simple technologies. At the same time, competitors can be encouraged to strengthen technical exchanges through cooperation. This should be conducive to simultaneously promoting the adoption of digital technologies among all participants.

(3) The lack of top management support and industry guidance is a core obstacle in some configurations and should be overcome. For top management support, exchanges and learning between senior leaders of enterprises should be organized, and training and learning of new technologies should be increased. This is so that they can understand the advantages of using digital technologies in major projects, have a deeper understanding of the adoption process of digital technologies and reduce their perceived complexity. In a similar vein, industry bodies and regulatory authorities should establish unified standards for the adoption of digital technologies that can be recognized by most organizations across the construction sector. For example, they must promote software interoperability standards, collaborative platform management standards, deliverables acceptance standards, and objective standards. All these standards guide the adoption of digital technologies in future major projects.

(4) Relative advantages, organizational needs, and participants' collaboration are the core factors in many cases of digital technologies adoption, though not always. The relative advantage of digital technologies can be achieved by strengthening research on digital technologies and advocating appropriate guidance according to government policies. Following technical research studies by academic institutions, both government and industry representatives can regularly organize publicity and exchange meetings on emerging digital technologies. Furthermore, the government should increase financial support for companies with pioneering applications of digital technologies, formulate policy preferences for companies with limited sources of funds, and help reduce the costs of technology acquisition.

Additionally, the full synergy from the adoption of digital technologies in major projects almost always involves multiple participants. The positive benefits of adopting digital technologies can only be harnessed when multiple industrial companies collaborate and effectively share data generated from models. Therefore, all participants should establish unified adoption mechanisms for digital technologies, focus on the whole process of collaboration, reasonably divide their labor to perform those tasks, and provide appropriate incentive mechanisms.

(5) Technical compatibility and organizational knowledge stock are marginal conditions and can be used as auxiliary tools to improve the adoption of digital technologies in major projects. Encourage major project participants to explore and pilot applications of digital technologies, and establish organizational models and workflows that match digital technologies to improve technical compatibility. Also, internal knowledge accumulation and external knowledge acquisition are two basic ways for organizations to increase their knowledge stock (Chen et al., 2018). Hence, each senior management participant in a major project should strengthen their employees' education and training level, and publicly share technologies adoption experiences to enhance the knowledge stock.

While the study identifies valuable conclusions, there are also some limitations. Firstly, due to the number of antecedent conditions identified, the data collected may not cover all combinations of antecedent conditions that exist in reality. That is, in the future, there is a need to focus on more important antecedent conditions to be determined as well as expand the number projects under investigation, and make the questionnaire sample size larger to improve the accuracy of the results.

Secondly, this study adopts a static configuration method, lacks continuous tracking of major projects, and cannot fully reflect the dynamic changes in the process of adopting digital technologies in major projects. In the future, based on the ideas proposed by Du (Du et al., 2021), there is therefore a need to track and investigate the participants of major projects, collect data at multiple time points, and further incorporate the time dimension into the analysis framework. This will enable further exploration of the antecedent pathway for digital technology adoption of major engineering projects from a dynamic perspective.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix I. Antecedents and consequence variables of the application of digital technologies in major projects

Category	Influencing factors	Interpretation	Representative references
Technology	Complexity (CE)	This refers to the extent to which digital technologies are perceived to be difficult to use.	(Gangwar, 2018) (Chen and Ni, 2019) (Ahuja et al., 2016)
	Interoperability (IA)	This refers to the extent to which the data generated by software related to digital technologies can be transmitted to other software without obstacles.	(You and Wu, 2019) (Jin et al., 2017) (Siebelink et al., 2018)
	Compatibility (CA)	This refers to the matching of digital technologies with the business processes, infrastructure, supply channels, company culture, and values of major project participants.	(Nnaji et al., 2018), (Gangwar, 2018) (Chen and Ni, 2019; Ullah et al., 2021)
	Relative advantages (RA)	This refers to the major project participants who will adopt and do not use digital technologies to compare, and believe that the use of digital technologies has advantages.	(Gangwar, 2018) (Lai et al., 2018) (Gangwar and Date, 2016)
Organization	Organizational needs (ON)	This refers to the degree of demand from major project participants for the adoption of digital technologies.	Tallon et al. (2019)
	Top management support (TMS)	This refers to the degree of support of the top management of the major project participants in the adoption of digital technologies, and the degree of their participation in digital technologies activities.	(Gangwar, 2018) (Lai et al., 2018) (Ifinedo, 2011)
	Knowledge stock (KS)	This refers to the technical knowledge, or tacit knowledge, required by major project participants to implement digital technologies. This includes the overall level of knowledge of the members and their receptivity to the adoption of digital technologies.	Zhang et al. (2020)
	Resource readiness (RR)	This refers to the resources prepared by major project participants for the adoption of digital technologies, including human resources, materials, information, and other resources, to measure the ability of internal resources of the organization to embrace the adoption of digital technologies.	(Abed, 2020) (Lai et al., 2018)
	Participants' collaboration (PC)	This refers to the degree to which digital technologies are adopted by the participants in major projects and the level of digital technologies collaboration between the participants.	(Li and Liu, 2019) (Andersson et al., 2016)
Environment	Industry guidance (IG)	This refers to the degree of perfection of contracts, adoption standards, and specifications related to the application of digital technologies in the construction industry.	(Alshamaila et al., 2013) (Bilal et al., 2016)
	Competitive pressures (CP)	This refers to the amount of pressure from competitors in the same industry to adopt digital technologies.	(Gangwar, 2018) (Alshamaila et al., 2013)
Outcome	Adoption of digital technologies in major projects (ADTMP)	This refers to whether the participants in major projects have applied digital technologies in major projects and whether they are willing to adopt them.	Ahuja et al. (2016)

Appendix II. The basic information of representative major projects

Project name	Province	Type	Digital technologies involved
Zhengji High-speed Railway (Henan Section)	Henan Province	Railway	Digital simulation, intelligent vision, intelligent robots, and the Internet of Things
Xi'an urban underground comprehensive pipe gallery	Shaanxi Province	Underground pipe gallery	Intelligent sensors, Internet of Things, automation control, GIS geographic information, 3D visualization
Shanxi Taiyuan East Second Ring Expressway	Shanxi Province	Highway	Full life cycle BIM technology for design, construction, construction, O&M

Appendix III. Sample distribution

Features	Classification	Sample size	Proportion (%)
Age	20–30	47	30.32
	31–40	58	37.42
	41–50	50	32.26
Unit nature	Real estate developer	14	9.03
	Design units	38	24.52
	Construction companies	63	40.65
	Supervisory unit	30	19.35
	Operating units	10	6.45
Years of service	1–5 months	11	7.1
	6 months to 1 year	24	15.48
	1–3 years	43	27.74
	4–10 years	46	29.68
	More than 10 years	31	20
Educational background	Junior colleges	46	29.68
	Undergraduate	50	32.26
	Master	29	18.71
	Doctor	30	19.35
Position Level	General staff	46	29.68
	Grassroots managers	47	30.32
	Middle management	31	20

(continued on next page)

(*continued*)

Features	Classification	Sample size	Proportion (%)
	Top management	31	20
Knowledge of digital technologies	Knows a little	8	5.16
	Average	33	21.29
	Understand	55	35.48
	Very knowledgeable	59	38.07

Appendix IV. Reliability and validity test results

Conditions	Question item	Factor loads	α coefficient	AVE	CR
Complexity (CE)	CE1	0.712	0.730	0.511	0.758
	CE2	0.719			
	CE3	0.714			
Interoperability (IA)	IA1	0.729	0.706	0.545	0.706
	IA2	0.748			
Compatibility (CA)	CA1	0.739	0.736	0.541	0.702
	CA2	0.732			
Relative advantages (RA)	RA1	0.710	0.813	0.503	0.835
	RA2	0.746			
	RA3	0.696			
	RA4	0.715			
	RA5	0.677			
Organizational needs (ON)	ON1	0.709	0.722	0.502	0.752
	ON2	0.706			
	ON3	0.711			
Top management support (TMS)	TMS1	0.763	0.741	0.519	0.812
	TMS2	0.723			
	TMS3	0.691			
	TMS4	0.702			
Knowledge stock (KS)	KS1	0.681	0.837	0.507	0.837
	KS2	0.771			
	KS3	0.705			
	KS4	0.725			
	KS5	0.674			
Resource readiness (RR)	RR1	0.765	0.710	0.541	0.702
	RR2	0.705			
Participants' collaboration (PC)	PC1	0.757	0.755	0.546	0.706
	PC2	0.720			
Industry guidance (IG)	IG1	0.758	0.714	0.546	0.706
	IG2	0.719			
Competitive pressures (CP)	CP1	0.762	0.749	0.544	0.704
	CP2	0.712			
Adoption of digital technol. in major projects (ADTMP)	ADTMP1	0.762	0.782	0.540	0.701
	ADTMP2	0.706			

Appendix V. Calibration values for each antecedent condition and outcome

Antecedent conditions and outcome	Full membership threshold	Crossover point	Full non-membership threshold
Complexity	3.654	1.923	0.192
Interoperability	3.666	1.929	0.193
Compatibility	3.611	1.900	0.190
Relative advantage	3.662	1.928	0.193
Organizational needs	3.720	1.958	0.196
Top management support	3.557	1.872	0.187
Knowledge stock	3.584	1.887	0.189
Resource readiness	3.619	1.905	0.190
Participants' collaboration	3.648	1.920	0.192
Industry guidance	3.576	1.882	0.188
Competitive pressures	3.701	1.948	0.195
Appl. of digital technol. in major projects	3.672	1.933	0.193

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