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An FsQCA and NCA Analysis on the Drivers and Comprehensive Impact Analysis of the Implementation of Digital Twins

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ABSTRACT

The adoption of digital technology is one of the key processes in the digital transformation of China's construction industry. As a representative digital technology in the digital transformation process of Construction 4.0, digital twin technology has attracted widespread attention in various fields, and its practical application is also growing rapidly. However, its implementation in the construction industry (CI) still faces major challenges. Although previous studies have made significant progress in understanding the drivers and barriers to the implementation of digital twins (DTs) in the CI, these studies have neglected to explore the comprehensive impact of various factors, and the configuration relationship between them remains unclear. This study uses a quantitative method to conduct a questionnaire survey to obtain 33 case sample data. Necessary condition analysis (NCA) and fuzzy set qualitative comparative analysis (FsQCA) methods are used for antecedent configuration analysis. The results show that: (1) The successful deployment of DTs in the CI does not depend on any single determinant, but is the adaptive result of the synergistic effect of multiple antecedent variables; (2) Six critical factors affecting the implementation of DTs in China's CI are identified, which can be summarized into four different causal paths or configurations, which are conducive to the implementation of DTs in China's CI. This study further explores and clarifies the comprehensive impact of antecedent variables on the implementation of DTs in China's CI provides a reference for the practice of digital transformation in the CI.

1. Introduction

Industrialized construction is considered critical for upgrading the construction industry (CI), particularly in developing countries like China [1]. The Chinese government has prioritized the implementation of industrialized construction for the modernization of the construction sector. However, there are barriers and risks associated with industrialized construction, including skill shortages and a lack of knowledge about off-site construction. To address the persistent challenges of low productivity and underperformance in construction projects, scholars and experts in the fields

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of construction, engineering, and architecture have been searching for optimal solutions [2,3]. Scholars have conducted studies to further understand these challenges [4].

The Industrial Revolution 4.0, also known as Industry 4.0, is an attempt to improve machine-to-machine interconnectivity and productivity. It uses current advancements in information and communication technology (ICT) to drive innovation across a wide range of fields. Regarded as a "high fidelity virtual replica of the physical asset with real-time two-way communication for simulation purposes and decision-aiding features for product service enhancement," digital twins (DTs) are a prevalent Industry 4.0 manufacturing technology. DTs provide an affordable method for resource tracking, scenario simulations, and solution creation. They are frequently regarded as flexible and scalable solutions.

Recently, there has been an increase in interest in the application of DTs systems in construction from both industry and academia [5]. The adoption of DTs can completely change the CI and has demonstrated a great deal of significance and vitality in other industries. Because of this, the construction sector needs to be adaptable and seize the chances presented by DTs apps and other digital technology. The only way CI can stay with other industries is in this manner [6]. The idea of a "smart society" and the growth of "Digital China" have become national strategic priorities. The groundwork for building a digital society has been established by the rapid development of new technologies, such as 5G, AI, and the Internet of Things. As a result, China has the necessary infrastructure and strong incentive to actively encourage the use of DT in the building sector [7].

Although DTs have anticipated advantages in CI applications, their practical applications remain limited [8]. Industry practitioners and researchers are also divided over how DTs assist in building and civil infrastructure project design and construction. This hinders a thorough understanding of and preparedness for digital technologies [9]. This phenomenon might be due to several reasons, such as limited incentives for innovation, the insufficiently demonstrated advantages of digitization, and businesses' reluctance to take on the risk of introducing innovation. Scholars have conducted research on such issues and examined the drivers that affect DTs implementation. These surveys, primarily based on interviews and literature review analysis, teased out some of the factors affecting DTs implementation and made significant progress in understanding the drivers of DTs implementation in the CI. However, they mainly adopted qualitative methods, and the research method adopted single-factor analysis. The comprehensive impact of various factors has been ignored, and the configuration relationship and mutual influence between the factors are still unclear. To fill this gap, this study used a quantitative method to conduct a questionnaire survey on the implementation of DTs in China's CI.

This study first explores the critical driving factors and configurations that affect the implementation of DTs in China's CI based on the TOE framework and the literature on the driving factors that affect the implementation of DTs. Specifically, a configuration model of the driving factors of DTs was established through research, and the TOE framework was used to analyze the comprehensive impact of these driving factors on China's CI. The FsQCA method was used to identify and analyze the complex interdependencies behind the development of DTs within the TOE framework, aiming to further explore and clarify the comprehensive impact of antecedent variables on the implementation of DTs in China's CI.

The remainder of this paper is organized as follows. The literature is reviewed in Section 2. The data analysis and techniques are presented in Sections 3 and 4. Section 5 discusses the data analysis findings. The conclusion is reported in Section 6.

2. Literature Review

2.1 Definition of Digital Twin

The concept of digital twins is not new, and previous studies have provided various definitions of DTs [10]. However, these definitions are application-based and are not limited to any specific industry (Table 1). These definitions in subsequent publications over the years do indicate a common theme: no matter which industry DTs are applied to, they should include physical entities, virtual entities, and the data that connects them. Michael Grieves published a white paper as early as 2014 that further clarified the concept of digital twins. Now, multiple factors have come together to bring the concept of digital twins to the forefront as a disruptive trend(the citation data in Table 1 is derived from the citation data of this literature displayed by WOS, which only indicates that although digital twins originated from applications in the aviation industry, their applications have expanded to different professional fields), but it is important to remember that "data that connects the physical and digital worlds and the two-way dynamic interaction of physical objects and virtual models are the key elements of digital twins." It is also important to remember that physical components are necessary to identify virtual entities as DTs.

Table 1
Definitions of the digital twins concept in literature

Authors	Definition	Research Fields	No. of Citation
Tuegel *et al.,* [11]	"The Digital Twin is a reengineering of structural life pre diction and management that utilizes the growing very h igh-performance computational infrastructure."	Engineering	1127
Glaessgen and Stargel [12]	"A digital twin is an integrated multi-physics, multi-scale, probabilistic simulation of a complex product that replicates its corresponding twin's existence using the best physical models, sensor updates, and other available technologies. "	Computer Science	2471
Rosen *et al.,* [13]	"The very accurate simulations of the process's current state and how it interacts with its surroundings in the real world—often referred to as the "Digital Twin"—must be accessible to the autonomous systems."	Manufacturing	1039
Grieves and Vickers [14]	"A collection of virtual information constructions known as the "Digital Twin" completely characterize a hypothetical or real physical manufactured good from the micro atomic to the macro geometrical levels."	Computer Science	2795
Liu *et al.,* [15]	In order to replicate the life of its corresponding flying twin, a digital twin is an integrated multiphysics, multiscale, probabilistic simulation of a vehicle or system as-built that makes use of the finest physical models currently available, sensor updates, fleet history, etc."	Healthcare	245
Khajavi *et al.,* [16]	"Because digital twins allow data to be transmitted seamlessly between the real and virtual worlds, they will make it easier to monitor, comprehend, and optimize the functioning of all physical entities—living and non-living."	Engineering (Building)	187

Qi *et al.,* [17]	"With digital modeling (DT), a physical thing is transformed into a virtual model that may be used to mimic its behaviours, track its current state, identify internal and external complications, spot anomalies, reflect system performance, and forecast future trends."	Manufacturing	979
Li *et al.,* [18]	"By using digital techniques to create a virtual product that, in both its exterior and internal characteristics, is similar to the actual item. To enable the interchange of data and information, a link is built between virtual and physical spaces."	Manufacturing	248

2.2 Digital Twin of the Construction Industry

The term "digital twin" covers a variety of digital technologies that exhibit unique characteristics in various industrial applications [19]. In recent years, there has been growing interest in the academic and industrial sectors regarding the use of DTs systems in construction. Owing to the lack of cyber-physical connectivity, the construction industry is often considered inefficient and low in productivity, with development opportunities that are frequently noted being labor management, digital technology integration, on-site execution, logistics management, and design and engineering procedures [20]. DTs have emerged as critical facilitators for the development of Construction 4.0, as sophisticated representations and computational models are necessary for improved building and construction solutions to yield insightful and intelligent data.

Digital twin systems combine virtual and physical data at every stage of the product lifecycle. DTs can be present at any stage of a product's lifespan, from conception to design. This produces a "physical twin," which is a digital representation of the real system. Digital Twin activities may enhance AEC-FM operations by improving data management and processing using large-scale data, information, knowledge integration, and synchronization. It dynamically integrates data and information throughout the lifespan of an asset. Combining a virtual information model with real-time data might significantly improve decision making over the entire building's lifespan. The integration of real-time data via IoT sensors and devices on the physical system enhances adaptive updating to serve the information for further machine learning and artificial intelligence integration to coordinate and automate the physical counterpart of the digital model, following operational changes [21].

Therefore, further exploration of the role of DTs as a comprehensive technology platform that seamlessly integrates other Industry 4.0 technologies lays the foundation for Construction 4.0, defined as a means to find a consistent complementarity among major emerging technological approaches in the CI [22].

The construction sector, in comparison to other industries, is currently trailing in its adoption of DTs. It is imperative to recognize and harness the potential and opportunities that DTs offer to the CI to expedite transformative progress within the sector. In this context, it will be beneficial to summarize research on DTs and their primary features and definitions, and present motivators and barriers associated with their implementation in the CI. Additionally, guiding potential improvements and implementations will contribute to development [23].

2.3 The Factors Affecting Implementing Digital Twins in the Construction Industry

Relevant research indicates that technology, enterprises, and institutions are related to digital transformation and play a comprehensive driving role. Through a literature review, it was found that the driving role of different factors can be explained from the perspectives of technology, organization, and environment [24]. Tornatzky and Fleischer developed the TOE framework to better understand how emerging technologies are adopted. The TOE framework describes the primary organizational, technological, and environmental elements affecting the uptake of emerging technologies. Governments and businesses have used the TOE framework to explain why developing technologies are being adopted. The TOE framework has also been used to examine the adoption of digital technology. The TOE framework is helpful for researching and understanding digital technology adoption behavior, as previously mentioned [25].

Technology-Organization-Environment (TOE) Model believes that the process of an organization adopting and implementing innovative technology is three primary factors—organization, technology, and external environment—that have an impact. Technical variables mostly relate to the features of the technology itself, including its relative benefits, compatibility, observability, and complexity. The scope and size of the organization and the features of the management structure are all considered organizational elements. The economic and cultural context in which the organization operates, as well as external pressure and competition, are all considered external environmental influences. The TOE model is a popular tool for analyzing the application background aspects of organizational technology in many information system areas. It considers all three factors that impact the adoption of information technology [25].

Based on the TOE Model, this study constructs a framework to examine the motivational factors that affect the adoption of DTs in the three contexts of technology, organization, and environment in China's CI. Figure 1 illustrates the research model. As shown in the figure, the conditional variables include the following six components:

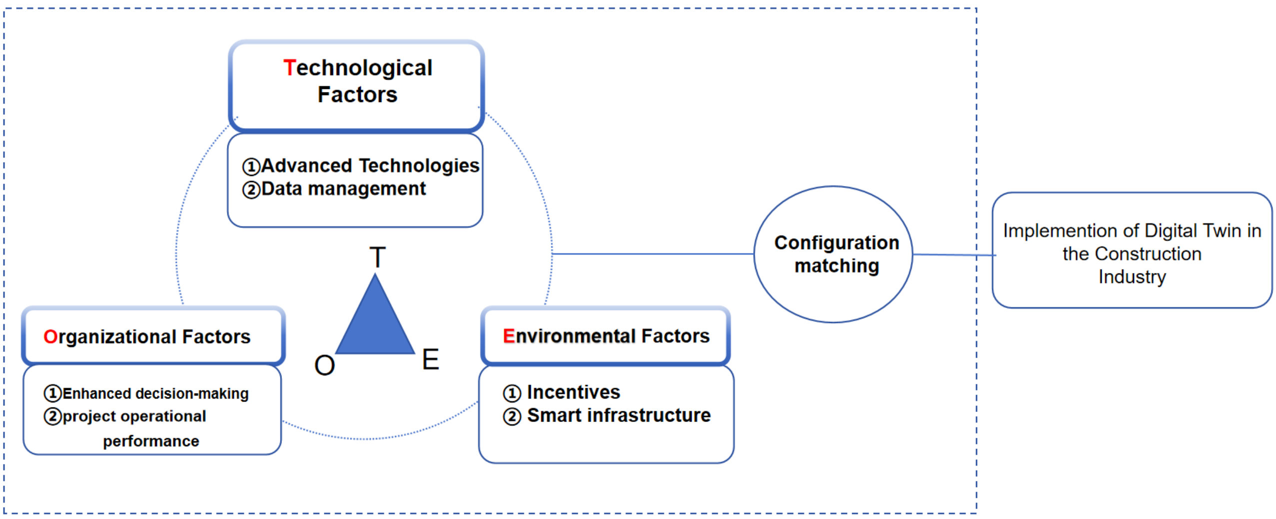

Fig. 1. Proposed research model based on the T-O-E framework

2.3.1 The technological factors

Technical factors refer to the combination of various technological drivers and the effective use of data [26], including advanced technologies and data management.

Advanced technologies: Research has shown that DTs, represented by the integration of BIM, IoT, and real-time predictions, can aid the building construction process [2]. The previous research listed more than a dozen technologies for DTs applications, such as wireless sensor networks (WSN), the Internet of Things (IoT), blockchains, and data mining [5]. The implementation of DTs not only requires the coordinated development of various digital technologies, but research also proves that it requires the integration of systems [27].

Data Management: Massive volumes of data will be generated by the integration of DTs enablers, which when gathered and incorporated into the platform will allow a wide range of stakeholders to communicate throughout the building process [27]. Building life cycle management, encompassing the design, construction, and operations phases, has made extensive use of data tagging systems (DTs) possible owing to its ability to facilitate smooth collaboration among professionals in the fields of Architecture, Engineering, and Construction (AEC) [2].

2.3.2 The organizational factors

Here, the organization mainly refers to the role of stakeholders, who often decide on organizational changes in construction companies, which will be a decisive factor in creating a more suitable environment for the industry's transformation to digital [28], including project operational performance and enhanced decision-making.

Enhanced decision-making: DTs offer the opportunity to create digital models and forecast the state and condition of physical assets both now and in the future. To improve decision making on the condition of physical assets, real-time prediction, optimization, monitoring, and control can be achieved by simulating these models. Facility managers can use it to make critical decisions concerning the operation and maintenance of building projects, in addition to making judgments about which information and components to retain or discard during project redesign and reengineering [29].

Project operational performance: As defined by DTs, digital models can produce, modify, and verify data based on real-life scenarios, thereby helping solve problems between different stakeholders and reducing disputes between them about the project [6]. Moreover, the application of DTs can improve the safety status of employees in construction projects and identify some safety issues [30]. From the life cycle perspective, by giving stakeholders enough information on the project, DTs not only help leverage enormous amounts of data to lower construction costs, increase quality, and boost effective stakeholder management. DTs can also assist with various management tasks during the building phase, including scheduling, quality control, material and resource management, and sequence management [6]. Exploring the impact of DTs such as the one mentioned above on performance and conducting project operational performances on the adoption of Construction 4.0 technologies is essential to convince decision-makers to adopt advanced technologies [28].

2.3.3 The environmental factors

Environmental factors emphasize the impact of environmental pressures and characteristics on the adoption of emerging technologies [25], including incentives and smart infrastructure.

Incentives: The adoption of new technologies requires increased operating costs [28,31]. For example, implementing digital technologies in China requires significant investment in technology infrastructure, including sensors, data collection, and analysis tools [32]. Some studies have pointed out that the integration of BIM and IoT has led to the emergence of DTs [2]. Therefore, some companies' existing BIM-based foundation is an incentive for them to implement DTs, and they can use their previous implementation experience to promote the implementation of DTs. However, the Chinese government has corresponding subsidies for the implementation of new digital technologies [7].

Smart infrastructure: the research mentioned some of the non-technical difficulties faced in the development and adoption of DTs in smart infrastructure systems [33]. At the same time, the purpose of the study is to bring stakeholders together to jointly develop digital twins through intelligent system framework research, which is crucial for the implementation of comprehensive array twins.

2.3.4 Outcome variable

Implementation of DTs in CI: In recent years, scholars have proposed different perspectives and viewpoints on the implementation of DTs. The most comprehensive summary is the six-step implementation process proposed by Deloitte: (1) imagination and complexity. This section mainly determines the appropriate application scenarios of DTs. (2) Identification of a suitable process. According to the technical infrastructure conditions and organizational management factors, the digital configuration that can reflect the highest implementation value of DTs is determined. (3) Pilot DTs. Using pilots as samples to accelerate skill improvement and repeat training to maximize the initial return on incentives. (4) Industrialize the process. Based on existing digitalization, the pilot digital scenarios are industrialized to ensure the applicability of the scenarios developed by the DTs. (5) The twin is scaled. Based on the pilot, technical standards, manuals, etc. to ensure the continuous expansion of development application scenarios; (6) monitor and measure. The implementation plan was monitored, and the results were used to effectively evaluate the implementation effect of DTs to ensure the best value. To make the process and objectives clear and concise for easy understanding, this study uses a four-layer framework to measure the outcome variable of DTs implementation: (a) DTs are used to create virtual simulation models of buildings; (b) real-time feedback of physical entity activity information and manipulation; (c) DTs virtual simulation functions are used to predict what will happen in the project; (4) solutions are improved and implementation strategies are optimized [34].

3. Methodology

This study uses Qualitative Comparative analysis (QCA) to investigate the variables influencing the application of DTs in China's CI. Quantitative analysis it differs from qualitative analysis in that it works with numerical data or data that able to be translated to numbers [35]. The benefits of both qualitative and quantitative research are combined in Larkin's groundbreaking QCA method, which breaks down the barriers between the two fields. Conventional case studies find it challenging to condense the interplay of several components or the possible association between various case combinations. However, the Fuzzy-set (FsQCA) method overcomes these inaccuracies in conventional case studies [36]. By setting relationships and path combinations, the specific impact paths of multiple indicators of the driving factors can be associated [37]. Precisely because the reality that affects the implementation of DTs is complex, a single factor can have a certain impact with a high probability. To depict the real situation as realistically as possible, this study uses the FsQCA method to extract the impact of DTs in China from complexity theory. Necessary paths for CI implementation to derive concepts and opinions that differ from earlier research. Figure 2 shows the specific implementation steps.

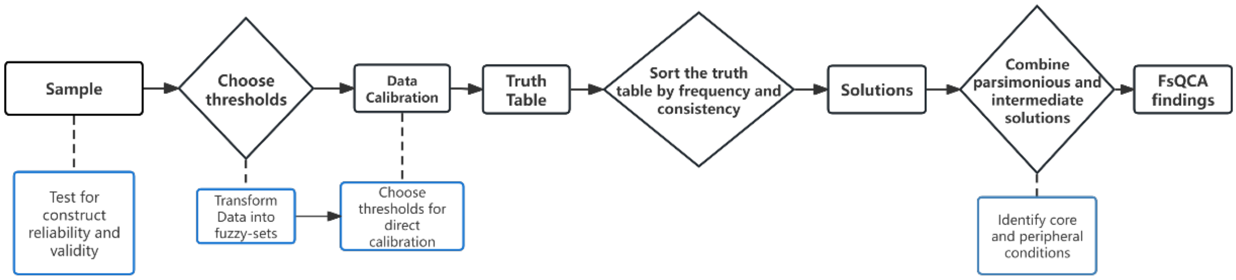

Fig. 2. Basic steps in FsQCA

3.1 Implementation content of FsQCA research method

Regarding sample size determination, one study by Marx [38] pointed out that the sharp increase in cases in QCA analysis does not allow researchers to obtain sufficient case knowledge, making it impossible to conduct a dialogue between theory and data. For 50 cases, the upper limit of the conditions was seven. On the other hand, the essence of QCA analysis is a method that enables researchers to calculate multiple solutions for multiple types of users, rather than using the best explanation to calculate the vast majority of solutions. The purpose of this study is to discover a trend. Therefore, as a study with a small sample size, this study collected 40 questionnaires from China's CI and selected 33 sample cases for analysis.

Because the questionnaire uses a five-point Likert scale to collect data, when imported into the FsQCA analysis software, multiple variables must first be merged into first-level indicator variables.

3.2 Choose thresholds

The data calibration stage is the most crucial stage in FsQCA. For a variable measured with numerous elements, a value must be computed before it can be entered into the FsQCA. It is important to emphasize that the FsQCA does not test the reliability and validity of the constructs; it only represents an analytical method. Therefore, after the questionnaire was collected, its reliability and validity were verified using SPSS according to traditional methods before the FsQCA analysis [39]. Data calibration can be direct or indirect. Researchers may choose to calibrate measurements in different ways, depending on what is being studied [40]. Therefore, the use of the direct method is recommended. This is a typical approach. The full set membership degree, full set non-membership degree, and intermediate set membership degree are represented by the three values that the researcher sets. This might result in more thorough research that is simpler to confirm and duplicate because the way thresholds are chosen is clearer [39].

3.3 Calibration of the data in the FsQCA software

This study adopted the direct calibration method. Because the questionnaire uses a five-point Likert scale, its threshold values are 4, 3, and 2 [39]. The values 0.95, 0.50, and 0.05 can be selected as the three thresholds (or breakpoints) that will change the data to calibrate it. Figure 3 presents the calibration results for all variables. The above operation is actually the fuzzification of the data.

A	B	C	D	E	F	G	H
RANK	A_c	B_c	C_c	D_c	E_c	F_c	DV_c
1	0.51	0.51	0.51	0.51	0.51	0.51	0.51
2	0.88	0.95	0.12	0.23	0.08	0.51	0.51
3	0.82	0.77	0.92	0.77	0.86	0.65	0.77
4	0.73	0.99	0.88	0.14	0.51	0.14	0.14
5	0.88	0.92	0.82	0.51	0.14	0.51	0.95
6	0.88	0.95	0.88	0.92	0.92	0.86	0.86
7	0.92	0.92	0.62	0.86	0.23	0.23	0.51
8	0.95	0.92	0.92	0.77	0.65	0.86	0.99
9	0.95	0.92	0.92	0.95	0.92	0.95	0.86
10	0.95	0.95	0.95	0.95	0.86	0.77	0.86
11	0.95	0.95	1	1	1	1	1
12	0.95	0.99	0.97	0.95	0.65	1	1
13	0.95	0.97	0.95	0.86	0.92	0.95	0.92
14	0.97	1	0.95	0.95	0.95	0.95	0.99
15	0.95	0.77	0.92	0.65	0.77	0.95	0.86
16	0.92	0.99	0.95	0.95	0.99	1	0.51
17	0.92	0.95	0.88	0.86	0.86	0.92	0.99
18	0.99	1	0.99	0.99	0.99	0.99	1
19	0.95	0.99	0.62	0.95	0.95	0.99	0.99
20	0.97	0.95	0.95	1	0.95	0.95	0.95
21	0.99	1	0.88	0.03	0.65	0.97	0.08
22	0.73	0.35	0.51	0.35	0.92	0.23	0.97
23	0.98	0.99	0.62	0.35	0.35	0.92	1
24	0.99	0.92	0.98	0.77	0.92	0.97	1
25	1	0.65	0.82	0.92	0.77	0.77	0.86
26	1	0.51	0.95	0.86	0.86	0.99	1
27	1	1	0.95	0.86	0.86	0.92	0.95
28	1	1	1	0.97	1	1	1
29	1	1	1	1	1	1	1
30	1	1	1	1	1	1	1
31	1	1	1	1	1	1	1
32	1	1	1	1	1	1	1
33	1	1	1	1	1	1	1

Fig. 3. The dataset after calibration

Note:
A; Advanced Technologies,
B; Data Management**,**
C; Enhanced decision-making,
D; Project operational performance,
E; Incentives**,**
F; Smart infrastructure**,**
DV: Implementing DTs in the CI.

4. Data Analysis and Result

4.1 Necessary Analysis

The FsQCA software examines the prerequisites for high and low DT implementations based on the correlation function. Validity and explanatory power were correlated with consistency and coverage, respectively. The "coverage" result indicates the extent to which cases with matching conditions and specific results are covered, while the "consistency" result indicates the percentage of cases that exhibit a certain result in the set of cases with corresponding conditions. The necessary conditions were analyzed through the truth table of FsQCA to determine the causal configuration of the conditions related to the outcome [40]. Necessity analysis was used to determine which variables were prerequisites for any outcome to occur, applying a recommended consistency value threshold of > 0.9 [41]. As indicated in Table 2, advanced technologies, Data Management, Enhanced decision-making, and smart infrastructure are considered necessary conditions for the good implementation of DTs (consistency is more than 0.9). These results show the complexity of the factors affecting the implementation of digital twins. Technology, organizational, and environmental conditions affect the implementation of DTs in a variety of ways.

Table 2
Results of one-factor necessity analysis

Condition Variables	High		Low	
	Consistency	Coverage	Consistency	Coverage
Advanced technologies	0.978	0.893	0.974	0.158
~Advanced technologies	0.079	0.944	0.342	0.733
Data Management	0.940	0.884	1	0.167
~Data Management	0.115	1	0.306	0.472
Enhanced decision-making	0.925	0.912	0.918	0.160
~Enhanced decision-making	0.148	0.910	0.497	0.540
Project operational performance	0.883	0.956	0.624	0.120
~Project operational performance	0.187	0.737	0.771	0.538
Incentives	0.871	0.937	0.740	0.141
~ Incentives	0.202	0.815	0.672	0.480
Smart infrastructure	0.923	0.942	0.803	0.145
~Smart infrastructure	0.163	0.823	0.680	0.610

Note: HIGH means that the digital twins are well implemented; Low means that the digital twins are not well implemented.

4.2 Conditional Configuration Analysis

According to the above truth table, every potential arrangement (or mix) that could occur is calculated. Theoretically, there are 2^k multifactor combination paths, where k represents the number of outcome predictors (six are discussed in this study). Therefore, this study uses fsQCA 3.0 software to conditionally configure the driving factors that affect DTs. Three types of answers can be found: parsimonious, intermediate, and complex [42]. Because there may be many sophisticated solutions, interpreting them can be challenging and, for the most part, impractical. Consequently, they underwent additional simplification into sets of parsimonious and intermediate solutions. Finally, intermediate solutions were reported ("solution" refers to configuration combinations that are supported by a large number of cases) [39]. The parsimonious solution set is a simplified version of the complex solution, based on simplifying assumptions, and presents the most important conditions that cannot be left out of any solution. This study focused on the analysis of intermediate solutions based on previous research results and guidance manuals [39].

Combining parsimonious and intermediate solutions can provide a more thorough and comprehensive understanding of the research findings [25] (Table 3). Because the consistency data of LOW in this solution is only 0.17<0.8, it is judged that there is no actual corresponding situation in the selected case conditions. Therefore, only the multi-factor path of HIGH is analyzed and explained below.

Table 3
Multi-factor combination path analysis of implementing DTs

	Configurations			
	H1	H2	H3	H4
Advanced technologies	●	●	●	●
Data Management	●		●	●
Enhanced decision-making	●	●		●
Project operational performance		⊗	⊗	●
Incentives		●	⊗	⊗
Smart infrastructure	●	⊗	●	
Consistency	0.948	0.876	0.939	0.977
Raw coverage	0.854	0.093	0.149	0.163
Unique coverage	0.680	0.010	0.015	0.010
Solution consistency	0.933			
Solution coverage	0.889			

Note: • = Core causal condition present; ⊗ = core causal condition absent; • = peripheral causal condition present; ⊗ = peripheral causal condition absent; "Blank" indicates that the condition may or may not appear in the path.

The results show that the four configuration paths H1, H2, H3, and H4 can drive better implementation of DTs. The threshold value was not exceeded by the necessary and adequate consistency of the six single variables and their opposite values. Consequently, no single element is adequate on its own. which inevitably leads to the implementation of DTs. In other words, it depends on the adaptive results of synergistic interactions between multiple prerequisite variables. The overall solution coverage was 0.889, which indicates that these four solutions currently cover a large part of the results under the influence of these six drivers.

Configuration H1: Configuration H1 shows that regardless of the project operational performance and incentive situation, as long as the factors of advanced technologies, Data Management, and Enhanced decision-making are strong, DTs can be well implemented. The unique consistency of H1 was 0.948, covering 85.4% of the cases and explaining 68% of the results alone.

Configuration H2: Configuration H2 shows that regardless of the degree of Data Management, when there are strong advanced technologies, enhanced decision-making, and incentives, even if the driving force of project operational performance and smart infrastructure is not very obvious, it can better promote the implementation of DTs. H2 leads to a consistency of 0.876, covers 9.3% of the cases, and explains only 1% of the outcome.

Configuration H3: Configuration H3 shows that regardless of the degree of enhanced decision-making, as long as there are strong advanced technologies, Data Management, and Smart infrastructure, the DTs can still be well implemented even if there is no explanation and support for the project operational performance and Incentives of the DTs. H3 leads to a consistency of 0.939, covers 14.9% of cases, and explains 1.5% of the outcomes alone.

Configuration H4: Configuration H4 shows that the good implementation of DTs is inseparable from the synergy of advanced technologies, Data Management, Enhanced decision-making, and project operational performance, even in the case of insufficient incentives. H4 led to a consistency of 0.977, covered 16.3% of cases, and explained only 1% of the outcome.

4.2 Robustness Test

This study used an adjustment of the consistency threshold to test the robustness of the results. The consistency threshold increased from 0.80 to 0.9, and other settings remained unchanged. The results obtained using fsQCA 3.0 software showed that there was no substantial change in the configuration. Therefore, it can be considered that the results passed the robustness test and that the empirical research results were reliable [39].

5. Discussion and Limitation

Based on the FsQCA method, this research conducted an in-depth analysis of the current status of DTs implementation in China's CI. The main conclusions are as follows: No core elements appear in the four combined paths, which means that the peripheral conditions in each path have a complementary influence.

First, Project operational performance has not had a decisive impact on the implementation of DTs from the surveyed cases. At present, from the perspective of literature and actual performance, the focus of DTs implementation in China's CI is still on technology integration and data management development. In recent years, some studies have begun to suggest that the focus of relevant decision-makers has gradually shifted from DTs to Project operational performance [28]. For developing countries such as China, CI is a pillar industry, and digital transformation is an effective way to promote productivity and quality. To better promote digital technology, the specific presentation of performance will make the implementation of DTs more explosive on the original basis. This study provides a direction for future research.

Second, no matter which combination path is used, the implementation of DTs in China's CI cannot be separated from the high level of advanced technologies, which fully demonstrates that technology integration is a strong fundamental condition and basic guarantee for the implementation of DTs. Under this premise, compared with incentives, factors such as data management and enhanced decision-making can better promote the implementation of DTs.

Third, the most surprising result of the study was the incentives. Its influence has been described in previous studies [28,31], but in the cases investigated this time, the influence of this factor is not obvious owing to the combined influence of other factors.

In summary, although in theory there are four configuration paths for DTs to perform well, from the data point of view, the coverage rate of the last three is extremely low, approximately 1%, indicating that there are very few such cases investigated in this study. The last three are characterized by incentives absent, which reflects the most real situation in China at present. For China, the impact of technology and organization is obviously more obvious and critical. Other countries can also analyze the problems of DTs implementation from different aspects based on this method and find improved solutions.

This study still has several shortcomings: (1) Due to the analytical characteristics of the FsQCA method, the impact of adding mediating variables cannot be considered in the analysis path; (2) As the life cycle of the construction project changes, the focus of DTs implementation will change. Future research could use dynamic methods to collect the latest case data and continue to explore the changes in factors affecting the implementation of DTs.

6. Conclusions

As a pillar industry of China's economy, the Chinese government has vigorously promoted the digital transformation of the construction industry to effectively improve its productivity and quality while reducing energy consumption and carbon emissions. As a representative digital technology in the digital transformation process of Construction 4.0, DTs have received widespread attention from various fields, and their practical applications are growing rapidly. Although previous research has made significant progress in understanding the drivers and barriers to the implementation of DTs in the CI, it has neglected to explore the comprehensive impact of various factors, and the configuration between them is still unclear. To further advance the implementation of DTs, this study focuses on how technology, organization, and environmental contexts can jointly create a path to achieve efficient implementation of DTs.

Using 33 valid case data collected in China, this study explored the combined paths of multiple driving factors behind the implementation of DTs in China’s CI based on the TOE framework and the FsQCA method. The findings revealed that: (1) the successful deployment of DTs within construction enterprises does not hinge upon any solitary determinant, but rather emerges as an adaptive outcome of synergistic interactions among multiple antecedent variables; (2) Using TOE as the theoretical framework, based on the literature review, six key driving factors affecting the implementation of DTs in China's CI were identified, which can be summarized into five different causal paths or configurations that are conducive to DTs adoption. (3) Four combined paths drive better implementation of digital twins. Advanced technologies are the basic guarantees for the four groups of paths. The four groups of paths that promote DTs implementation are alternatives. Specifically, data management, enhanced decision-making, project operational performance, and smart infrastructure can replace each other. However, from the perspective of case coverage, in actual situations, better implementation is mainly reflected in the coordination of advanced technologies, data management, enhanced decision-making, and smart infrastructure. (4) Four groups of combination paths lead to low-level implementation of DTs in the results, but because their consistency is less than 0.9, it is proved that such combination paths do not exist in this actual case. Because this time the configuration analysis is mainly based on the driving factors that affect the implementation of DTs, such corresponding results are produced. The isolated impacts of a single component are typically the focus of current research [42]. However, this study indicates that various configurations of several contextual condition variables, such as technological, organizational, and environmental factors, influence the adoption of DTs rather than a single element acting alone. As such, it offers an alternative and more thorough viewpoint for a deeper comprehension of the motivations for DT installation. Using the Technology Adoption Framework (TOE), which was developed based on earlier research, this study builds a thorough framework of the elements influencing the deployment of DTs from the standpoint of technology adoption, allowing for a clearer understanding of the interactions between different aspects. This study further explores and clarifies the role of the comprehensive impact of antecedent variables on the implementation of DTs in China's CI, enriches the research on antecedent factors of digital transformation in the CI, and provides a reference for the practice of digital transformation in the CI.

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References

[1]. Ji, Yingbo, Fadong Zhu, Hong Xian Li, and Mohamed Al-Hussein. "Construction industrialization in China: current profile and the prediction." *Applied Sciences* 7, no. 2 (2017): 180. https://doi.org/10.3390/app7020180

[2]. Deng, Min, Carol C. Menassa, and Vineet R. Kamat. "From BIM to digital twins: A systematic review of the evolution of intelligent building representations in the AEC-FM industry." *Journal of Information Technology in Construction* 26 (2021). https://doi.org/10.36680/j.itcon.2021.005

[3]. Santos, Luis, Simon Schleicher, and Luisa Caldas. "Automation of CAD models to BEM models for performance based goal-oriented design methods." *Building and Environment* 112 (2017): 144-158. https://doi.org/10.1016/j.buildenv.2016.10.015

[4]. Xiahou, Xiaer, Jingfeng Yuan, Yan Liu, Yuchun Tang, and Qiming Li. "Exploring the driving factors of construction industrialization development in China." *International journal of environmental research and public health* 15, no. 3 (2018): 442. https://doi.org/10.3390/ijerph15030442

[5]. Hu, Wei, Kendrik Yan Hong Lim, and Yiyu Cai. "Digital twin and industry 4.0 enablers in building and construction: a survey." *Buildings* 12, no. 11 (2022): 2004. https://doi.org/10.3390/buildings12112004

[6]. Opoku, De-Graft Joe, Srinath Perera, Robert Osei-Kyei, and Maria Rashidi. "Digital twin application in the construction industry: A literature review." *Journal of Building Engineering* 40 (2021): 102726. https://doi.org/10.1016/j.jobe.2021.102726

[7]. Liu, Chuncheng, and Ying Tian. "Recognition of digital twin city from the perspective of complex system theory: Lessons from Chinese practice." *Journal of Urban Management* 12, no. 2 (2023): 182-192. https://doi.org/10.1016/j.jum.2023.04.001

[8]. Shahzad, Muhammad, Muhammad Tariq Shafiq, Dean Douglas, and Mohamad Kassem. "Digital twins in built environments: an investigation of the characteristics, applications, and challenges." *Buildings* 12, no. 2 (2022): 120. https://doi.org/10.3390/buildings12020120

[9]. Opoku, De-Graft Joe, Srinath Perera, Robert Osei-Kyei, Maria Rashidi, Tosin Famakinwa, and Keivan Bamdad. "Drivers for digital twin adoption in the construction industry: A systematic literature review." *Buildings* 12, no. 2 (2022): 113. https://doi.org/10.3390/buildings12020113

[10]. Borth, Michael, Jacques Verriet, and Gerrit Muller. "Digital twin strategies for SoS 4 challenges and 4 architecture setups for digital twins of SoS." In *2019 14th annual conference system of systems engineering (SoSE)*, pp. 164-169. IEEE, 2019. https://doi.org/10.1109/SYSOSE.2019.8753860

[11]. Tuegel, Eric J., Anthony R. Ingraffea, Thomas G. Eason, and S. Michael Spottswood. "Reengineering aircraft structural life prediction using a digital twin." *International Journal of Aerospace Engineering* 2011, no. 1 (2011): 154798. https://doi.org/10.1155/2011/154798

[12]. Glaessgen, Edward, and David Stargel. "The digital twin paradigm for future NASA and US Air Force vehicles." In *53rd AIAA/ASME/ASCE/AHS/ASC structures, structural dynamics and materials conference 20th AIAA/ASME/AHS adaptive structures conference 14th AIAA*, p. 1818. 2012. https://doi.org/10.2514/6.2012-1818

[13]. Rosen, Roland, Georg Von Wichert, George Lo, and Kurt D. Bettenhausen. "About the importance of autonomy and digital twins for the future of manufacturing." *Ifac-papersonline* 48, no. 3 (2015): 567-572. https://doi.org/10.1016/j.ifacol.2015.06.141

[14]. Grieves, Michael, and John Vickers. "Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems." *Transdisciplinary perspectives on complex systems: New findings and approaches* (2017): 85-113. https://doi.org/10.1007/978-3-319-38756-7_4

[15]. Liu, Ying, Lin Zhang, Yuan Yang, Longfei Zhou, Lei Ren, Fei Wang, Rong Liu, Zhibo Pang, and M. Jamal Deen. "A novel cloud-based framework for the elderly healthcare services using digital twin." *IEEE access* 7 (2019): 49088-49101. https://doi.org/10.1109/ACCESS.2019.2909828

[16]. Khajavi, Siavash H., Naser Hossein Motlagh, Alireza Jaribion, Liss C. Werner, and Jan Holmström. "Digital twin: vision, benefits, boundaries, and creation for buildings." *IEEE access* 7 (2019): 147406-147419. https://doi.org/10.1109/ACCESS.2019.2946515

[17]. Qi, Qinglin, Fei Tao, Tianliang Hu, Nabil Anwer, Ang Liu, Yongli Wei, Lihui Wang, and Andrew YC Nee. "Enabling technologies and tools for digital twin." *Journal of Manufacturing Systems* 58 (2021): 3-21. https://doi.org/10.1016/j.jmsy.2019.10.001

[18]. Li, Lianhui, Bingbing Lei, and Chunlei Mao. "Digital twin in smart manufacturing." *Journal of Industrial Information Integration* 26 (2022): 100289. https://doi.org/10.1016/j.jii.2021.100289

[19]. Singh, Maulshree, Rupal Srivastava, Evert Fuenmayor, Vladimir Kuts, Yuansong Qiao, Niall Murray, and Declan Devine. "Applications of digital twin across industries: A review." *Applied Sciences* 12, no. 11 (2022): 5727. https://doi.org/10.3390/app12115727

[20]. You, Zhijia, and Lingjun Feng. "Integration of industry 4.0 related technologies in construction industry: a framework of cyber-physical system." *Ieee Access* 8 (2020): 122908-122922. https://doi.org/10.1109/access.2020.3007206
[21]. Hosamo, Haidar Hosamo, Aksa Imran, Juan Cardenas-Cartagena, Paul Ragnar Svennevig, Kjeld Svidt, and Henrik Kofoed Nielsen. "A Review of the Digital Twin Technology in the AEC-FM Industry." *Advances in civil engineering* 2022, no. 1 (2022): 2185170. https://doi.org/10.1155/2022/2185170
[22]. Forcael, Eric, Isabella Ferrari, Alexander Opazo-Vega, and Jesús Alberto Pulido-Arcas. "Construction 4.0: A literature review." *Sustainability* 12, no. 22 (2020): 9755. https://doi.org/10.3390/su12229755
[23]. Kozlovska, Maria, Daria Klosova, and Zuzana Strukova. "Impact of industry 4.0 platform on the formation of construction 4.0 concept: a literature review." *Sustainability* 13, no. 5 (2021): 2683. https://doi.org/10.3390/su13052683
[24]. Verhoef, Peter C., Thijs Broekhuizen, Yakov Bart, Abhi Bhattacharya, John Qi Dong, Nicolai Fabian, and Michael Haenlein. "Digital transformation: A multidisciplinary reflection and research agenda." *Journal of business research* 122 (2021): 889-901. https://doi.org/10.1016/j.jbusres.2019.09.022
[25]. Chen, Shuangying, Qiyue Li, Bo Lei, and Na Wang. "Configurational analysis of the driving paths of Chinese digital economy based on the Technology–Organization–Environment framework." *Sage Open* 11, no. 4 (2021): 21582440211054500. https://doi.org/10.1177/21582440211054500
[26]. Rasheed, Adil, Omer San, and Trond Kvamsdal. "Digital twin: Values, challenges and enablers from a modeling perspective." *IEEE access* 8 (2020): 21980-22012. https://doi.org/10.1109/ACCESS.2020.2970143
[27]. Ozturk, Gozde Basak. "Digital twin research in the AECO-FM industry." *Journal of Building Engineering* 40 (2021): 102730. https://doi.org/10.1016/j.jobe.2021.102730
[28]. Shafei, Hazwani, Afiqah R. Radzi, Mohammed Algahtany, and Rahimi A. Rahman. "Construction 4.0 technologies and decision-making: A systematic review and gap analysis." *Buildings* 12, no. 12 (2022): 2206. https://doi.org/10.3390/buildings12122206
[29]. Opoku, De-Graft Joe, Srinath Perera, Robert Osei-Kyei, Maria Rashidi, Keivan Bamdad, and Tosin Famakinwa. "Barriers to the adoption of digital twin in the construction industry: A literature review." In *Informatics*, vol. 10, no. 1, p. 14. MDPI, 2023. https://doi.org/10.3390/informatics10010014
[30]. Hou, Lei, Shaoze Wu, Guomin Zhang, Yongtao Tan, and Xiangyu Wang. "Literature review of digital twins applications in construction workforce safety." *Applied Sciences* 11, no. 1 (2020): 339. https://doi.org/10.3390/app11010339
[31]. Opoku, De-Graft Joe, Srinath Perera, Robert Osei-Kyei, Maria Rashidi, Tosin Famakinwa, and Keivan Bamdad. "Drivers for digital twin adoption in the construction industry: A systematic literature review." *Buildings* 12, no. 2 (2022): 113. https://doi.org/10.3390/buildings12020113
[32]. Junjia, Yin, Aidi Hizami Alias, Nuzul Azam Haron, and Nabilah Abu Bakar. "A Bibliometrics-Based systematic review of safety risk assessment for IBS hoisting construction." *Buildings* 13, no. 7 (2023): 1853. https://doi.org/10.3390/buildings13071853
[33]. Broo, Didem Gürdür, Miguel Bravo-Haro, and Jennifer Schooling. "Design and implementation of a smart infrastructure digital twin." *Automation in construction* 136 (2022): 104171. https://doi.org/10.1016/j.autcon.2022.104171
[34]. Agrawal, Ashwin, Martin Fischer, and Vishal Singh. "Digital twin: From concept to practice." *Journal of Management in Engineering* 38, no. 3 (2022): 06022001. https://doi.org/10.1061/(ASCE)ME.1943-5479.0001034
[35]. Ong, Siew Har, Sai Xin Ni, and Ho Li Vern. "Dimensions Affecting Consumer Acceptance towards Artificial Intelligence (AI) Service in the Food and Beverage Industry in Klang Valley." *Semarak International Journal of Machine Learning* 1, no. 1 (2024): 20-30. https://doi.org/10.37934/sijml.1.1.2030
[36]. Pappas, Ilias O., Patrick Mikalef, Michail N. Giannakos, and Panos E. Kourouthanassis. "Explaining user experience in mobile gaming applications: an fsQCA approach." *Internet Research* 29, no. 2 (2019): 293-314. https://doi.org/10.1108/IntR-12-2017-0479
[37]. Jiao, Jian-ling, Xiao-lan Zhang, and Yun-shu Tang. "What factors determine the survival of green innovative enterprises in China?--A method based on fsQCA." *Technology in Society* 62 (2020): 101314. https://doi.org/10.1016/j.techsoc.2020.101314
[38]. Marx, Axel. "Crisp-set qualitative comparative analysis (csQCA) and model specification: Benchmarks for future csQCA applications." *International journal of multiple research approaches* 4, no. 2 (2010): 138-158. https://doi.org/10.5172/mra.2010.4.2.138
[39]. Pappas, Ilias O., and Arch G. Woodside. "Fuzzy-set Qualitative Comparative Analysis (fsQCA): Guidelines for research practice in Information Systems and marketing." *International Journal of Information Management* 58 (2021): 102310. https://doi.org/10.1016/j.ijinfomgt.2021.102310

[40]. Rihoux, Benoît, and Charles C. Ragin, eds. *Configurational comparative methods: Qualitative comparative analysis (QCA) and related techniques*. Vol. 51. Sage, 2009. https://doi.org/10.4135/9781452226569
[41]. Cebotari, Victor, and Maarten P. Vink. "A configurational analysis of ethnic protest in Europe." *International Journal of Comparative Sociology* 54, no. 4 (2013): 298-324. https://doi.org/10.1177/0020715213508567
[42]. Fan, Xiaonan, Ye Wang, and Xinyuan Lu. "Digital transformation drives sustainable innovation capability improvement in manufacturing enterprises: Based on FsQCA and NCA Approaches." *Sustainability* 15, no. 1 (2022): 542. https://doi.org/10.3390/su15010542