scientific reports

Check for updates

OPEN

How to improve performance of Chinese BIM-supported civil engineering projects based on the qualitative comparative analysis method

Weiwei Zuo[1]✉, Tingting Mei[2]✉, Shuda Zhong[3], Xiaofan Jiang[4] & Ning Yan[1]

Building information modeling (BIM) demonstrates transformative potential in enhancing productivity within the architecture, engineering and construction industry. Nevertheless, determining how to improve the project performance through diverse BIM application conditions and identifying the performance improvement paths remains a valuable yet underexplored topic. Combined with the four actual application stages of BIM (the embryonic, the development, the stability, and the maturity stage) and five application conditions (BIM personnel training, BIM application points, BIM team building, BIM platform establishment, and BIM standard formulation), this study explores the performance improvement paths for Chinese BIM-supported civil engineering projects using the qualitative comparative analysis method. The findings indicate that none of the five application conditions constitutes a necessary condition for high project performance. The results reveal three configuration paths for enhancing comprehensive and individual performance: the talent-oriented path focusing on BIM personnel training and BIM team building, the technology-oriented path emphasizing BIM standard formulation, BIM platform establishment, and BIM application points, and the integrated path combining the talent-oriented path and the technology-oriented path. This paper not only can help the project stakeholders to allocate resources and improve performance for Chinese BIM-supported civil engineering projects but also provides a reference for government-related policies.

Keywords Construction management, Project performance, Building information modeling (BIM), Qualitative comparative analysis (QCA), Improvement path

The architecture, engineering and construction (AEC) industry is a key driver of China's economy, currently facing many challenges related to competitiveness, labor shortages, energy efficiency, and productivity[1]. China's AEC industry has made considerable contributions to the country's overall gross domestic product (GDP) with a total current price of over $ 1.18 trillion in 2024 according to China's National Bureau of Statistics data. Building information modeling (BIM) technology has significantly expanded in the AEC industry[2]. However, the application of information technology in this industry is very slow and still being explored.

BIM technology has significant advantages in improving project productivity and performance in the AEC industry[3,4], and can bring huge improvements for stakeholders, such as consultants and contractors[5]. BIM can reduce construction project cost and time by integrating a parameterized digital model as an information support[6,7]. The four major contributions of BIM include improved accuracy, better collaboration, appropriate schedule, and higher efficiency[8]. BIM technology not only ensures construction quality, safety, and environmental friendliness[9], but also realizes risk management during the construction stage, including risk monitoring, identification, and assessment[10]. For instance, Abanda et al. revealed that BIM has greater benefits in off-site manufacturing than in traditional construction technology by considering a series of parameters[11,12]. The application of BIM technology with building energy modeling (BEM) can reduce the energy consumption of

[1]School of Civil Engineering, Architecture and Environment, Hubei University of Technology, Wuhan, China. [2]School of Civil Engineering and Architecture, Wuhan Institute of Technology, Wuhan, China. [3]Hubei Communications Planning and Design Institute Co., Ltd., Wuhan, China. [4]Shanghai BaiTong Project Management Consulting Co. Ltd., Shanghai, China. ✉email: whutzuo@126.com; 22243571@qq.com

buildings in the operational phases[13]. Guo et al. introduced a compression technique for mechanical, electrical, and plumbing (MEP) models, and the sizes of the models can be reduced substantially[14].

Although there exists literature on the benefits of BIM application that BIM can improve civil engineering project performance, to date, researchers have not obtained convincing quantitative evidence that BIM application will lead to improved project performance[15]. This is due to the following reasons: (1) Most previous studies focus on developing tools or methods to evaluate the impact of risk on project performance with few consideration of management issues involved in the application of BIM[16,17]; (2) The use effect of BIM technology involves five conditions (including BIM personnel training, BIM application points, BIM team building, BIM platform establishment, and BIM standard formulation). BIM technology can break traditional information fragmentation and optimize workflow, change organizational relationships, and therefore involve management level issues; (3) It is difficult to accurately measure the influence of BIM application on project performance of a single project[15]; (4) The schedule, the cost, and the quality, being the indicators of project performance, are both interdependent and independent of each other; thus, it is more meaningful to use their comprehensive indicators to measure project performance[18,19]; (5) The previous research methods are mainly based on the traditional deductive methods (e.g., structural equation modeling (SEM), multi-linear regression (MLR)), which focus on the net benefit between BIM technology application conditions and civil engineering project performance[15,20]. In other words, most studies attempt to examine the relationship between BIM application and civil engineering project performance by considering one factor or class of factors. However, these studies underestimate that BIM application is the integration of positive or negative responses under various conditional interactions and do not systematically analyze the integration of diverse application conditions, much less the influence of different combinations on the performance of civil engineering projects[21]. To solve the above research gap, this paper adopts an abductive method, the qualitative comparative analysis (QCA), to study the complex causal connection between the BIM technology application conditions and the civil engineering project performance from the configuration perspective, aiming to find out the performance improvement path of civil engineering project using BIM from the management level of BIM application conditions and provide suggestions for BIM-supported project performance improvement in the four actual application stages of BIM.

Thus, this paper measures the five application conditions of BIM technology and the civil engineering project performance (including schedule, cost, and quality) and their combinations. According to the multi-stage development of BIM technology, this paper adopts datasets of 36 practical BIM-supported civil engineering project cases in regions with different heterogeneity in BIM development[22], to systematically study how to improve the civil engineering project performance through different application conditions of BIM technology from the perspective of configuration and find out the performance improvement paths of Chinese BIM-supported civil engineering projects.

Literature review and propositions

Project performance

Performance improvement of civil engineering projects is one of the main objectives of the AEC industry. Recent research has made considerable progress in linking superior project performance to BIM applications[23]. Several findings show that the effective application of BIM can directly improve project performance[24]. Relevant research can be summarized in the following four aspects:(1) Improvement of the level of collaboration across disciplines and teams[25,26]; (2) Assistance in the life cycle management of buildings[27]; (3) Improvement of the cost, schedule, and quality performance of civil engineering projects[28,29]; (4) Promotion of the integration of new technologies[30]. To sum up, it is difficult to accurately measure the impact of BIM application on project performance of a single project. The schedule, the cost, and the quality, being the indicators of project performance, are both interdependent and independent of each other; thus, it is more meaningful to use their comprehensive indicators to measure project performance. Therefore, this paper proposes the following proposition:

Proposition 1 (Outcome variable) *The application of BIM technology can improve the performance of civil engineering projects, including cost, schedule, and quality*.

Antecedent conditions for BIM technology application

BIM personnel training (BIM-PT)

The shortage of professionals is one of the key factors that poses a significant hindrance to the application of BIM technology in the AEC industry[22]. China's vast AEC industry is currently in the midst of a transition towards the adoption of BIM technology. Training can lead to behavioral changes to avoid the risk of stakeholders falling back on traditional behavior[31]. The adoption of model transformations without proper training leads to a misunderstanding of BIM, thereby extending the transition period[8]. Moreover, BIM and 3D modeling training can enrich the knowledge of subcontractors and consultants to enhance their competitiveness[32]. However, BIM Personnel Training (BIM-PT) mainly faces two major problems: achieved immediately and additional investment[33]. The lack of skilled personnel and required training in BIM significantly hinders BIM application[34]. Personnel training plays a fundamental role in promoting the effective application of BIM[35]. Previous studies have indicated that the lack of skilled personnel and the absence of knowledge and training in Building Information Modelling (BIM) are one of the main challenges hindering the adoption of BIM in the architecture, engineering, and construction (AEC) industry. Therefore, this study proposes the following proposition:

Proposition 2 (Condition 1) *BIM-PT is one of the antecedent conditions for using BIM to improve the performance of civil engineering projects*.

BIM application points (BIM-AP)
Given the relatively extensive application of BIM throughout the project life cycle, most buildings use BIM in multiple applications, and almost half of the projects use it as a modeling tool[8]. The integration of BIM and lifecycle management PLM shows the unique advantages of lifecycle management and cross-regional collaboration[36]. Although the overall BIM adoption has improved, its implementation is often decentralized rather than being based on project-wide collaboration. The reasons originated from four main factors: (1) the owner is an important entity in promoting BIM application in projects and his willingness to apply BIM will eventually matter[37]; (2) BIM tools, as well as the lack of BIM knowledge, have obstructed its application[12]; (3) The more the involvement of stakeholders in BIM-supported projects and the higher the per-unit cost, the higher the BIM application rate will be[15]; (4) the broader participation across disciplines leads to greater BIM applications, leading to project's value increase, especially higher-complexity projects[15]. The building SMART (Specific, Measurable, Achievable, Realistic, and Timely) alliance summarizes 25 different applications of BIM in the AEC field in the US[38]. Considering the current application status of BIM and the civil engineering project delivery mode in China, this paper further subdivides the three cross-stage application points involved (including the Design Reviews, the 3D Coordination, and the Record Model) into six BIM technology application points. Given the significant contribution of China's AEC industry to the GDP and the slow adoption of information technology in the industry, the Chinese government is gradually promoting the application of BIM technology. Thus, this paper involves 28 BIM application points shown in Fig. 1, and proposes the following proposition:

Proposition 3 (Condition 2) *BIM application points (BIM-AP) is one of the antecedent conditions for using BIM to improve the performance of civil engineering projects.*

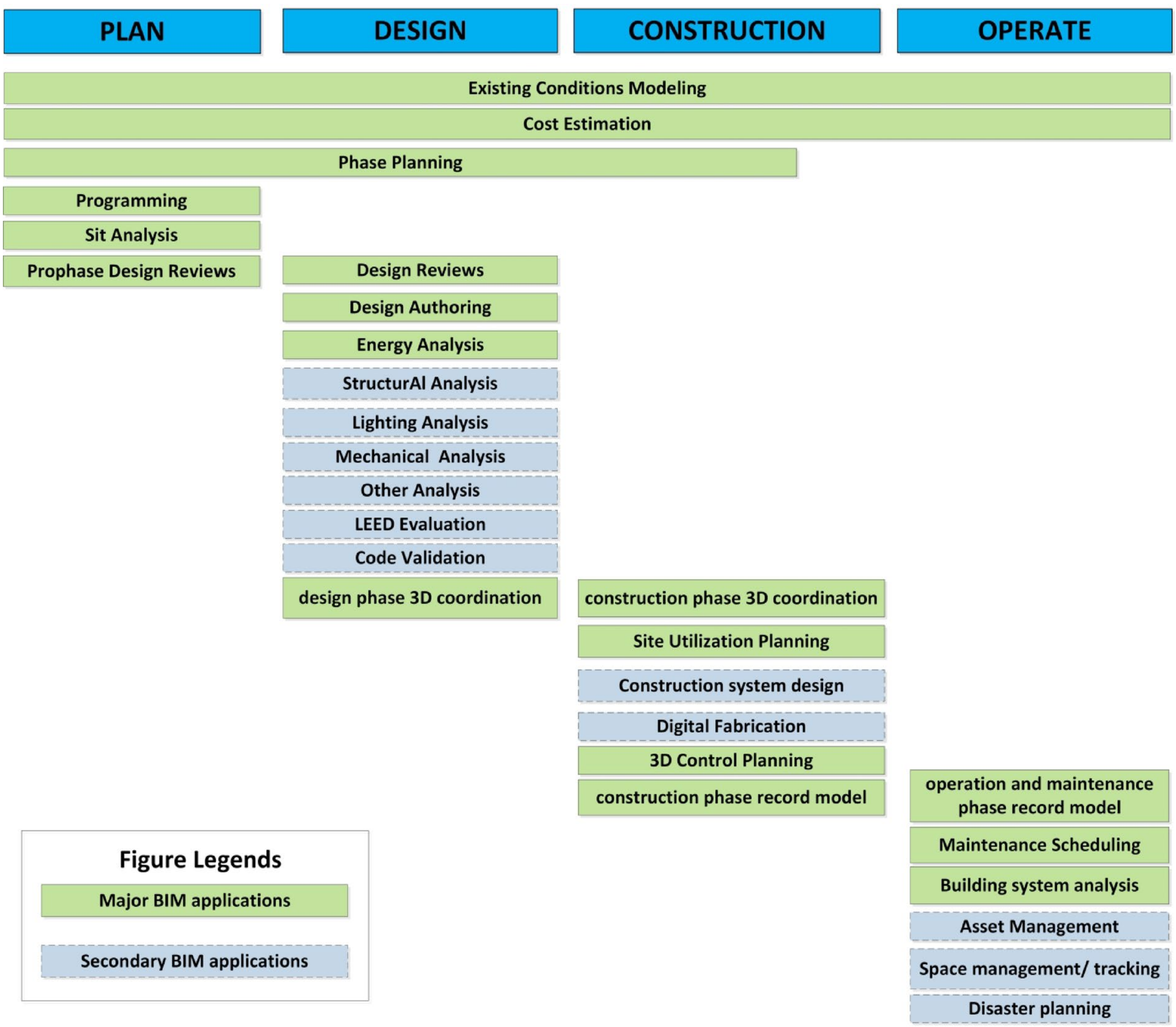

Fig. 1. BIM application points.

BIM team building (BIM-TB)
The success of the project is attained by improving the team performance; thus, high-quality teams are the basis for improving project performance and ensuring project success. When team members are actively engaged through high-quality interactions, the team will be more integrated, and such projects will have fewer delays and better quality[39]. Stakeholder management serves as a crucial and beneficial intermediary factor within the context of BIM implementation and project performance[24], whereas BIM also helps stakeholders deliver a better management view[26]. However, parties without any prior working relationship tend to depend on contract control to enhance performance, whereas those with an established relationship show a preference for contingency adaptation[40]. On the one hand, BIM facilitates the collaboration between the different project teams to enhance information sharing and overall performance by providing a BIM-supported network[41]. On the other hand, in a BIM-supported project network, the project stakeholders who hold more central positions are likely to exhibit a greater sense of responsibility and dedication, thereby contributing to enhanced project cooperation[42]. Although the personnel allocation of the BIM team is important, its influence on the civil engineering project productivity and performance has seldom been thoroughly investigated [43]. Team is the main operation primitive of integrated organization, which can realize achievements that individuals cannot do. A highly integrated design and construction team is more likely to control costs, give clients a better transition experience, and increase their perception of the system's quality. Therefore, this paper proposes the following proposition:

Proposition 4 (Condition 3) *BIM team building (BIM-TB) is one of the antecedents of using BIM to improve the performance of civil engineering projects.*

BIM platform establishment (BIM-PE)
Auxiliary tools can facilitate the achievement of engineering goals in conjunction with BIM hardware and software. However, the selection of inappropriate tools may diminish the value of information interaction between the model and management[8]. Furthermore, the implementation of BIM technology entails significant costs, including those associated with training and adapting workflows, as well as investments in necessary software and hardware[1]. Although some Chinese companies have reaped substantial benefits from using BIM tools, the development of BIM technology remains immature for several reasons: (1) Since foreign tools are not compatible with China's current situation, experts are emphasizing the use of Industry Foundation Classes IFC-based file conversion and data management to develop BIM applications[8]; (2) The development of BIM tools is not complete, requiring urgently the localization of BIM platform[8]. Moreover, the lack of project experience and software compatibility as well as the difficulty encountered in modeling management are three major factors affecting the implementation of BIM[44]. BIM tools currently face four major obstacles, including difficulties in data exchange, difficulties in choosing the appropriate tools, the insufficient functions, and the inadequate localization. Therefore, this paper puts forward the following proposition:

Proposition 5 (Condition 4) *BIM platform establishment (BIM-PE) is one of the antecedent conditions for using BIM to improve the performance of civil engineering projects.*

BIM standard formulation (BIM-SF)
The underlying risk factors for BIM technology include unclear data ownership, incomplete BIM standards, lack of insurance, changes in delivery patterns, software functionality issues, and so on[45]. Protocols and standards are used to prevent data loss to achieve better information sharing, information use (and reuse), coordination, and communication[46]. The insufficient research on BIM, particularly regarding standards and domestically oriented tools, may represent the most significant barrier to the practical application of BIM[47]. However, BIM standards and codes of practice differ between Chinese and international civil engineering projects. Moreover, the differences affect the flow of information and the collaboration among project stakeholders[30]. Since 2019, in response to the global trend of BIM adoption, China's Ministry of Housing and Urban-Rural Development has increased the number of BIM pilot projects to guide the extensive promotion of BIM. The central and local governments have formulated policies and standards for the application of BIM. Moreover, various industries and enterprises have also developed BIM standards, showing that China's BIM standard series is gradually improving under the guidance of government policies. To better organize and control the delivery of information in the BIM project, planning and delivery must be standardized. Therefore, this paper proposes the following proposition:

Proposition 6 (Condition 5) *BIM standard formulation (BIM-SF) is one of the antecedent conditions for using BIM to improve the performance of civil engineering projects.*

The shortcomings of the existing studies

Although there exist a few broader literatures on the benefits of BIM application that BIM can improve construction project's comprehensive performance and individual performance (e.g., cost, schedule, and quality), there are still some limitations in previous study on how BIM technology affects project performance. (1) Previous studies on BIM have focused on technology, in particular how BIM has the potential to positively impact project performance, with a focus on how some specific attributes associated with BIM affect project performance. (2) Due to the single object of the case study, the applicability of the case is limited. Most of the case study on the impact of BIM on project performance focus on the application of a single case, such as roads, bridges, water conservancy, ports, etc., demonstrating the feasibility and effectiveness of BIM technology. (3) When studying the causal relationship between the use of BIM and project performance, it is impossible to create generalized evaluation indicators. (4) The research method of causality is mainly based on the traditional deductive method (e.g., structural equation modeling, multi-linear regression, and Delphi method), which focus on the net benefit between BIM technology application conditions and construction project performance. However, BIM has not been widely used in China, it is difficult to obtain a sufficient number of BIM cases for traditional statistical analysis.

To sum up, the linear influence between BIM and project performance has only been studied based on the traditional deductive method, which focuses on the net effect between BIM and project performance, and the impact of combination effects BIM application conditions on project performance from the perspective of configuration has not been systematically studied. The point of departure of this study is to solve the above research gap, and systematically and comprehensively study the complex casual relationships between projects' comprehensive and individual performance (including cost, schedule, and quality) and five BIM application conditions (including BIM-PT, BIM-AP, BIM-TB, BIM-PE and BIM-SF) from the perspective of configuration. Based on the abductive method, the improvement paths of comprehensive and individual performance of Chinese BIM-supported civil engineering projects are identified.

Method and cases

Method and technical route

This study employs qualitative comparative analysis (QCA), an abductive approach, to examine the intricate causal linkages between the BIM application conditions and the performance of Chinese BIM-supported civil engineering projects. QCA method is distinct from structural equation modeling and multi-linear regression, which decompose cases into independent and dependent variables and concentrate on the net effect between them[48]. A review of previous cases of the use of QCA in architectural studies shows that this technique offers significant benefits when analyzing architectural project cases, particularly in scenarios where the quantity of accessible cases is restricted[49]. QCA performs a case-specific comparative analysis from a holistic perspective, regarding each case as the "configuration" of the condition variables[50]. Moreover, this tool compares several scenarios and the accompanying configuration that determines whether or not the outcome appears to determine the causal link between the conditional configuration and the outcome. QCA can leverage other methods in the following respects: (1) QCA concentrates on the intricate and asymmetric connection between the outcome and its preceding configurations; (2) The QCA method is suitable for research with small and medium-sized samples (< 50 cases); (3) Using QCA for data analysis, a combination of independent variables can be obtained, including variables that do not have significant effects; (4) QCA is capable of processing quantitative data, qualitative data that has been calibrated, and their combination[51]. Although the nature of the architectural organization is different from that of other fields, QCA has been used within and across the architecture, engineering, and construction industry.

The QCA method is extensively studied and applied in the field of project management. The research content covers various aspects including international projects, engineering enterprises, large-scale projects, project managers, and individual experiences. Regarding international projects, QCA has been used to study the key factors contributing to the compliance behavior of international construction contractors[52], and to explore the configuration effects of the three dimensions of sustainable delivery[53]. In terms of engineering enterprises, QCA is used to analyze issues related to the digital transformation of engineering enterprises[54], to study the synergistic effects between project characteristics and contract governance[55], and to assess the environmental, social, and governance (ESG) performance of Chinese construction enterprises[56], as well as to explore strategies for enhancing the organizational resilience of listed construction and engineering companies[57]. Regarding large-scale projects, QCA has been employed to study the intricate causal linkages that impact the success of mega civil engineering projects[58], to explore the safety resilience of large construction projects and their optimization paths[59], and to analyze the factors affecting the complexity of large projects, thereby obtaining governance strategies for managing the complexity of large-scale projects[60]. In terms of project managers and individuals, the QCA method is used to study the impact of project managers' and foremen's experience on project management success[61], as well as the complex relationships between BIM performance and user satisfaction[21]. Therefore, the QCA method is fully applicable to examine the intricate causal linkages between the BIM application conditions and the performance of Chinese BIM-supported civil engineering projects.

The results of QCA have the advantages of asymmetry, multiple concurrencies, and equivalence. QCA encompasses clear-set QCA, multi-values QCA, and fuzzy-set QCA. Clear-set QCA is used to process complex binary data sets, and fuzzy-set QCA is capable of handling a variety of data types, such as Likert-scale data, clickstream data, and multimodal data. At the same time, fuzzy-set QCA can be combined with binary variables (0/1) that do not need to be converted into fuzzy sets. The research framework is shown in Fig. 2.

Cases

According to related books, this paper calculates the following information about BIM engineering projects: (1) Project profile: type and name of projects; (2) BIM application information: BIM personnel training (BIM-PT), BIM application points (BIM-AP), BIM team building (BIM-TB), BIM platform establishment (BIM-PE), BIM standard formulation (BIM-SF); (3) Project performance indicators: actual completion of the project objectives (cost, schedule, quality). Note that a total of 137 BIM cases were collected and 36 cases with complete information from different regions were retained for follow-up analysis. The number of variables and cases that meet the small sample size requirements of QCA studies (10–40 cases, no more than 7 condition variables)[62]. The details of the cases are available in the Supplementary Materials Table S1.

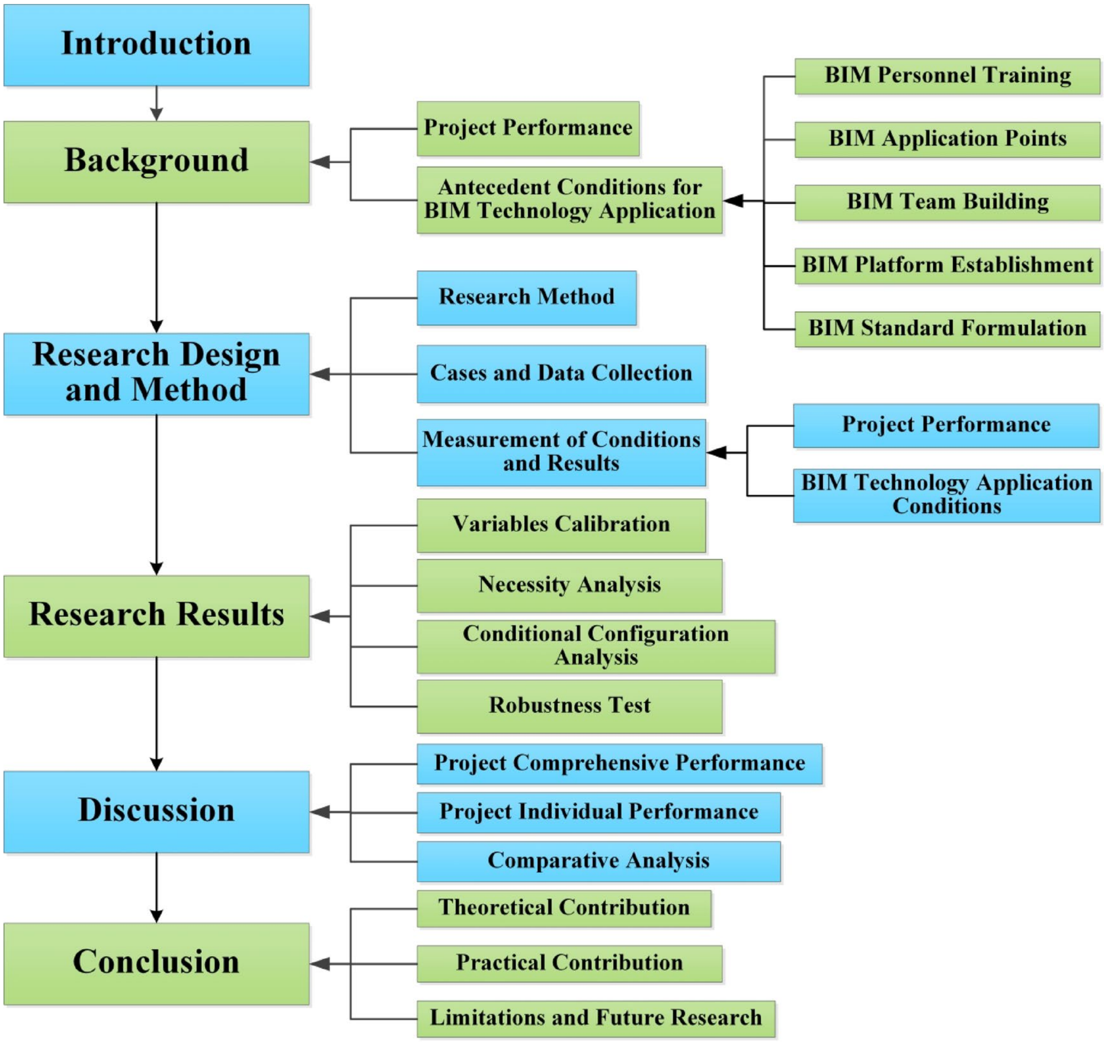

Fig. 2. Research framework.

Measurement of conditions and results

Measurement of results: project performance

This paper mainly studies the civil engineering projects' comprehensive performance, which considers the cost, the schedule, and the quality indicators. When the actual cost is less than or equal to the expected cost, the cost performance value can be assigned as 1; otherwise, it will be assigned to 0. When quality management is good, the value of quality performance can be assigned to 1; otherwise, it will be assigned to 0. Moreover, when the progress is delayed, normal, and advanced, the relative value is equal to −1, 0, or 1, respectively. Finally, the measured values of the cost, schedule, and quality are summed algebraically to show the overall comprehensive performance of the civil engineering project.

Measurement of BIM technology application conditions

For the four dimensions of BIM-PT, BIM-SF, BIM-TB, and BIM-PE, if they exist in the civil engineering project, their value will be 1; otherwise, it will be 0. Concerning the BIM-AP, if a civil engineering project has adopted all 28 BIM technology application points, it is assigned a value of 1. Otherwise, the ratio of the actual number of adopted BIM technology application points to 28 is used as the measure of the extent of BIM technology application points. Measurement standards for variables are shown in Table 1. Measurement results of project performance and BIM technology application conditions are available in the Supplementary Materials Table S2.

Since the values of the case data include clear sets and fuzzy sets, this paper needs to combine clear-set QCA and fuzzy-set QCA to study complex causal relationships between project comprehensive performance and individual performance and five BIM application conditions and determine the performance configuration improvement paths.

Research results

Variables calibration

The condition and result calibrations were divided into two types:

Variables	Measurement standards
Cost goal	Assign a value of 1 for cost savings, and 0 otherwise
Schedule goal	Assign values of − 1, 0, and 1 for schedule delayed, on-time, and advanced, respectively
Quality goal	Assign a value of 1 for quality compliance, and 0 otherwise
Comprehensive performance	The algebraic sum of the measured values of cost, schedule, and quality
BIM-PT	Assign a value of 1 for BIM-PT exist, and 0 otherwise
BIM-SF	Assign a value of 1 for BIM-SF exist, and 0 otherwise
BIM-TB	Assign a value of 1 for BIM-TB exist, and 0 otherwise
BIM-PE	Assign a value of 1 for BIM-PE exist, and 0 otherwise
BIM-AP	Assign a value of 1 for adopted all 28 BIM-AP, and the ratio of the actual number of adopted BIM technology application points to 28 otherwise

Table 1. Measurement standards for variables. BIM personnel training (BIM-PT), BIM team building (BIM-TB), BIM platform establishment (BIM-PE), BIM standard formulation (BIM-SF), BIM application points (BIM-AP).

- Condition variables such as BIM-PT, BIM-AP, BIM-TB, BIM-PE, and BIM-SF, and result variables such as quality goal and cost goal are assigned according to the 0/1 distribution where 1 is used when the targeted goal is present and 0 in case of its absence. Such variables do not need any calibration before being imported into fsQCA software;
- Making the descriptive statistics through SPSS, the percentiles 95%, 50%, and 5% of the variables, such as BIM-AP, the scheduled goal, and the comprehensive performance are set as "fully affiliated", "cross point", and "completely unaffiliated" anchor points respectively[63]. The anchor points of these three variables were calculated as (0.8005, 0.25, and 0.104), (1, 0, and − 1), and (3, 1, and − 0.15).

Finally, fsQCA software was used to calibrate data according to the full membership threshold of 0.95, the full non-membership threshold of 0, and the crossover point of 0.5. The data after calibration are shown in Table 2.

Necessity analysis

Based on the dataset's properties, fsQCA allows for identifying the necessary and sufficient conditions of the result. Specifically, if a condition set is a superset of the result set, then the condition is a prerequisite for the result. The necessary sub-set relation consistency is usually used as shown in Eq. (1).

$$Consistency\left(Y_i \le X_i\right) = \sum\left[min\left(X_i, Y_i\right)\right] / \sum\left(Y_i\right) \quad (1)$$

Y_i represents the outcome variables–project performance (including the project's comprehensive performance and individual performance focusing on cost, schedule, and quality); and X_i represents the condition variables (including BIM-PT, BIM-AP, BIM-TB, BIM-PE, and BIM-SF).

The necessary condition has a recommended consistency threshold of 0.9[64]. When comprehensive performance and individual performance are set as outcome variables and the consistency does not reach 0.9, it will be considered unnecessary. Analysis of antecedents' necessary condition is shown in Table 3.

Conditional configuration analysis

This study employs a truth table to investigate the influence of combined paths on the outcome variables. The configuration case frequency is set at 1, the raw consistency is set at 0.85[65], and the PRI is set at 0.85[66]. Through the standard analysis of the completed truth table, complex solutions, parsimonious solutions, and intermediate solutions can be derived. This paper opts for both intermediate and parsimonious solutions to elucidate the configuration path model. Thus, one can write: Completion of project goals = F (BIM-PT, BIM-AP, BIM-TB, BIM-PE, and BIM-SF). The configurations of antecedent variables are presented in Table 4. From Table 4, it can be observed that there are three comprehensive performance improvement paths, two cost reduction paths, four progress advance paths, and three quality promotion paths. When the comprehensive performance, cost, schedule, and quality act as the outcome variables respectively, the overall coverage and the overall consistency of solutions are relatively high.

Robustness test

The robustness test of QCA is necessary to examine whether the relevant outcome indicators change significantly under different operation choices. A solution term under a different choice of operations (e.g., case frequency, original consistency, PRI consistency) can be regarded as robust if it has a combination of conditions, consistency, and coverage similar to the original model[68]. This study adjusts the raw consistency level from 0.85 to 0.90[69], with comprehensive performance, cost, schedule, and quality serving as outcome variables. The results reveal that the configurations of the new models correspond with those of the original models, which implies that the modeling of the original models is relatively robust[70].

Case	BIM application points		Schedule		Comprehensive performance	
	Initial	After calibration	Initial	After calibration	Initial	After calibration
1	0.68	0.91	− 1	0.05	− 1	0.01
2	0.86	0.97	− 1	0.05	0	0.07
3	0.75	0.94	0	0.5	2	0.82
4	0.68	0.91	0	0.5	2	0.82
5	0.61	0.88	0	0.5	2	0.82
6	0.61	0.88	1	0.95	1	0.5
7	0.39	0.68	1	0.95	2	0.82
8	0.21	0.31	1	0.95	1	0.5
9	0.32	0.59	0	0.5	1	0.5
10	0.25	0.5	0	0.5	1	0.5
11	0.29	0.55	1	0.95	3	0.95
12	0.18	0.19	1	0.95	3	0.95
13	0.25	0.5	1	0.95	3	0.95
14	0.29	0.55	0	0.5	1	0.5
15	0.32	0.59	0	0.5	1	0.5
16	0.21	0.31	0	0.5	2	0.82
17	0.18	0.19	1	0.95	3	0.95
18	0.29	0.55	1	0.95	3	0.95
19	0.43	0.73	1	0.95	3	0.95
20	0.25	0.5	1	0.95	2	0.82
21	0.39	0.68	0	0.5	1	0.5
22	0.14	0.09	0	0.5	1	0.5
23	0.21	0.31	0	0.5	1	0.5
24	0.25	0.5	1	0.95	3	0.95
25	0.29	0.55	0	0.5	1	0.5
26	0.25	0.5	1	0.95	3	0.95
27	0.18	0.19	0	0.5	1	0.5
28	0.18	0.19	0	0.5	1	0.5
29	0.07	0.02	0	0.5	1	0.5
30	0.79	0.95	1	0.95	3	0.95
31	0.14	0.09	1	0.95	2	0.82
32	0.11	0.05	1	0.95	3	0.95
33	0.25	0.5	0	0.5	1	0.5
34	0.21	0.31	1	0.95	1	0.5
35	0.18	0.19	0	0.5	1	0.5
36	0.18	0.19	0	0.5	1	0.5

Table 2. Data before and after calibration.

Discussion

In light of the current development of BIM technology, this paper categorizes its evolution into four distinct phases, namely the embryonic stage, the development stage, the stability stage, and the maturity stage. Based on the configuration analysis, this paper reveals nine concurrent paths of individual performance improvement and three concurrent paths of comprehensive performance improvement, and these eleven paths involve three types of configuration paths (including the talent-oriented path, the technology-oriented path, and the integrated path), which also validated the Propositions 1–6. Among them, the talent-oriented path attaches importance to BIM personnel training and BIM team building, the technology-oriented path attaches importance to BIM standard formulation, BIM platform establishment, and BIM application points. Finally, the integrated path is the combination of the talent-oriented path and the technology-oriented path.

Project comprehensive performance

There are three different paths of project comprehensive performance improvement in BIM-supported projects, which proved that the application of BIM can improve performance through three paths. Team building can actively improve the comprehensive performance of the project during the embryonic stage. BIM improves the communication between team members and the information management of the project as the team members use BIM-supported processes and programs to achieve collaborative work from the embryonic stage[1]. As the development and stability stages are reached, the active promotion of the BIM team building should be

	Comprehensive performance		Cost		Schedule		Quality	
	CY	CE	CY	CE	CY	CE	CY	CE
BIM-PT	0.28	0.61	0.33	0.64	0.26	0.58	0.26	0.58
~ BIM-PT	0.72	0.68	0.67	0.56	0.74	0.72	0.74	0.72
BIM-SF	0.33	0.61	0.38	0.62	0.34	0.64	0.34	0.64
~ BIM-SF	0.67	0.69	0.62	0.57	0.66	0.70	0.66	0.70
BIM-PE	0.23	0.60	0.33	0.78	0.19	0.50	0.19	0.50
~ BIM-PE	0.77	0.68	0.67	0.52	0.81	0.73	0.81	0.73
BIM-TB	0.62	0.70	0.67	0.67	0.60	0.69	0.60	0.69
~ BIM-TB	0.38	0.61	0.33	0.47	0.40	0.65	0.40	0.65
BIM-AP	0.61	0.83	0.50	0.60	0.55	0.79	0.55	0.79
~ BIM-AP	0.65	0.84	0.50	0.57	0.67	0.84	0.67	0.84

Table 3. Analysis of antecedents' necessary conditions under multiple projects' performance. (~) signifies the absence or negation of the five application conditions. CY denotes the consistency between the five application conditions and performance improvement, while CE signifies the coverage between the five application conditions and performance improvement.

Configurations	Comprehensive performance			Cost		Schedule				Quality		
	ES	DS/SS	MS	ES	MS	ES	DS	SS	MS	ES	DS	SS
	A1	A2	A3	B1	B2	C1	C2	C3	C4	D1	D2	D3
BIM-PT	□		□	★	□	□	□	□	★	☆	□	□
BIM-SF	☆	☆	★	□	★	★	★	☆		☆	□	★
BIM-PE	□	□	★	□	■	■	□	□	☆	□	□	★
BIM-TB	★	★	☆	☆	☆	☆		★	■	★		☆
BIM-AP		■	★	□	★	■	☆		★		★	★
Raw coverage	0.25	0.20	0.04	0.04	0.05	0.04	0.11	0.24	0.11	0.28	0.24	0.04
Unique coverage	0.13	0.07	0.04	0.04	0.05	0.04	0.11	0.24	0.11	0.16	0.12	0.04
Consistency	0.85	0.97	1.00	1.00	1.00	1.00	1.00	0.82	0.97	1.00	0.95	1.00
Solution coverage	0.36			0.08		0.50				0.44		
Solution consistency	0.88			1.00		0.90				0.98		

Table 4. Configurations of antecedent variables with achievements of project performance. Annotation: ES, DS, SS, and MS correspond to the embryonic stage, the development stage, the stability stage, and the maturity stage of BIM application, respectively. The symbols "★" and "☆" denote the presence and absence of the core condition, which signifies the existence of a strong causal relationship between the five application conditions and the concerned performance outcome, respectively. The symbols "■" and "□" denote the presence and absence of the edge condition, which signifies a weak causal relationship between the five application conditions and the performance outcome, respectively. A blank indicates that the presence or absence of this condition does not affect the level of concerned performance outcome[67].

integrated, thus improving the openness of information and the comprehensive performance of the project[71]. Meanwhile, BIM technology improves the project's comprehensive performance by facilitating collaboration between project teams[41]. However, when BIM enters the maturity stage, BIM standards become necessary for improving work efficiency. The establishment of a comprehensive BIM standard system has a significant impact on the application of BIM and the willingness of stakeholders to engage in BIM-related projects[41]. With the development of BIM standards, BIM technology can realize the smooth and efficient transfer of information and data across the whole life cycle of each project process and role[72]. Moreover, by combining it with smart site standards, quality control standards, and safety management standards, BIM can improve the comprehensive performance of engineering projects[73]. Furthermore, the information interaction platform[74] and the high application level of BIM are also the core variables affecting project performance. Thus, when BIM moves from the embryonic stage to the maturity stage, the configuration type of high comprehensive performance path of the project will alter from the talent-oriented path to the technology-oriented path.

Project Individual performance

The individual performance involved in this paper mainly includes project cost, schedule, and quality. Each of these parameters will be determined in detail hereafter.

Project cost

There are two different paths of project cost reduction in BIM-supported projects, which prove that the application of BIM can reduce project costs. The embryonic stage pays more attention to BIM personnel training. Despite the necessity for extra investment in new technologies and training in the embryonic stage[75], the cultivation of talents, in the long run, will bring greater benefits to the enterprise due to the learning curve and training curve in training. Moreover, in the maturity stage, BIM standard formulation, BIM application points, and BIM platform establishment can reduce project costs. BIM common technical standards are essential to redress the technological burden on design office requirements to prevent overlapping investments. More BIM application points will contribute to cost reduction[76]. BIM-supported collaborative work platform consists of multi-professional participation and coordination, which can minimize the problems caused by materials, equipment, and costs in the process of project implementation to reduce project costs[74]. Therefore, when BIM changes from the embryonic stage to the maturity stage, the configuration type of the project cost reduction will change from the talent-oriented path to the technology-oriented path.

Project schedule

There are four different paths of project advanced progress in BIM-supported projects, which prove that the application of BIM can advance project progress through four combinations. The embryonic and development stages pay more attention to BIM standard formulation. Once the standard is defined and set, it will guide the project management team and have a strong impact on all decisions in the project[77]. Moreover, unifying standards and improving efficiency would help in speeding up the project schedule[78]. Furthermore, BIM platform establishment and BIM application points in the embryonic stage will also be conducive to progress control. In fact, in the early stage, the platform establishment can effectively realize data sharing and resource saving, to promote the progress of the whole project[74]. With the transition of BIM from the development stage to the stability stage, and given that the existing BIM platform has already met the requirements, enterprises no longer focus on the establishment of BIM platforms. In contrast, the stability stage focuses more on BIM team building. Adequate project team capacity, capability, organization, and planning are needed for the successful delivery of BIM projects[71]. For the successful delivery of BIM projects, it is essential that the project team possesses adequate capacity, organization, and planning. In the maturity stage, BIM personnel training, BIM team building, and BIM application points can promote the project schedule. The lag of people's learning process usually leads to a more significant learning effect in later stages. Therefore, the early effect of BIM personnel training on schedule control is non-obvious due to the needed time for training[44]. The contribution to the engineering project without delay will also be of the maximum value after the late staff training is certified and the project personnel's BIM abilities have been considerably improved[79]. Project personnel who are proficient in the use of a wider range of BIM applications will take charge of the project schedule[27], and specific control points will facilitate effective progress tracking to ensure that tasks are implemented in practice in line with this schedule[80]. Therefore, when BIM moves from the embryonic stage to the maturity stage, the configuration of the project schedule will change from a technology-oriented path to an integrated path.

Project quality

There are three different paths of project quality promotion in BIM-supported projects, which proved that the application of BIM can enhance project quality through three combinations. In the embryonic stage, BIM team building can improve project quality, and the BIM team is capable of reducing the time required for model checking and enhancing the quality of BIM collaboration management work[81]. Besides, BIM can help construction organizations improve project quality, optimize the efficiency of collaboration, and reduce construction cycle and costs[82]. During the development stage, BIM application points are more important to improve project quality. The application of BIM is positively correlated with project delivery speed, team cohesion, and facility quality[15]. The more the BIM application points are, the higher the BIM application degree will be, and the better the quality control effect on the project will also be[83]. In addition to BIM application points, the BIM platform establishment and the BIM standard formulation are also conducive to the improvement of project quality during the stability stage. The application of BIM platform is critical to the demand of BIM quality control[84]. The minimum criteria for BIM quality management are essential to ensure that quality control remains a central focus[73]. One of the primary barriers to BIM adoption is the lack of industry-wide BIM standards, and the significant advantages of BIM adoption are enhancements in design and project quality[85]. Therefore, at the level of project quality, BIM moves from the embryonic stage to the stability stage, and the configuration type of quality promotion alters from the talent-oriented path to the integrated path.

The performance improvement paths

Based on the above performance analysis results, the following performance improvement paths of Chinese BIM-supported civil engineering projects can be drawn:

- The comprehensive performance improvement path A1 in the embryonic stage is similar to the quality improvement path D1, indicating that quality improvement in the embryonic stage plays a major role in comprehensive performance improvement.
- The comprehensive performance improvement path A3 in the maturity stage is similar to the cost reduction path B2 in the maturity stage and the quality improvement path D3 in the stability stage, showing that the improvement of the comprehensive performance in the maturity stage is primarily attributed to the interaction between cost and quality factors. Among them, the role of quality improvement is relatively advanced, which begins to affect comprehensive performance improvement in the stability stage.
- The comprehensive performance improvement path A2 in the development stage and the stability stage consists of the integration of the schedule in advance path C3 in the stability stage and the quality improvement path D2 in the development stage, which shows that the comprehensive performance improvement in the development stage and the stability stage is mainly affected by the advance of schedule and the quality improvement. Compared to the quality improvement, the effect of schedule in advance is relatively lagging.

Conclusion

Although BIM has wide applications in AEC fields, the relationships between BIM application conditions and projects' performance remain unclear. This paper explores the relationships between BIM application conditions and project performance based on abductive QCA method systematically and comprehensively. Based on the configuration perspective, this paper reveals three types of performance improvement paths in the four stages of BIM development through QCA. In other words, under different combinations of BIM application conditions, BIM can improve civil engineering projects' comprehensive and individual performances by focusing on cost, schedule, and quality.

Theoretical contribution

On the one hand, this study not only extends from the single index to multifaceted indexes of civil engineering project performance but also considers the effect of five aspects of BIM application conditions and their combinations on multifaceted projects' performance from a configuration perspective. On the other hand, it introduces the development level of BIM in four stages and proposes configuration promotion paths for the comprehensive performance and the individual performance of civil engineering projects (e.g., talent-oriented path, technology-oriented path, and integrated path).

From a methodological standpoint, this paper not only compensates for the limitations of traditional deductive approaches (e.g., SEM and MLR), but also demonstrates that QCA is appropriate for examining the intricate causal relationship between the five BIM applications and the multiple dimensions of civil engineering project performance. Previous studies have focused on qualitative analysis or questionnaire analysis[15], with only a few based-on case studies, lacking sufficient quantitative evidence to prove that the BIM application is related to the multiple improvement performance. However, case-oriented QCA overcomes the traditional deductive analysis's shortcomings, such as only considering symmetry and net effect. In addition, QCA generates multiple equivalent paths where necessary and sufficient conditions are determined, to improve civil engineering project performance.

Although the research is based on Chinese cases, it also holds significant value for scholars around the world. Firstly, the QCA method and the analytical framework for the project performance are universal and can provide a reference for researchers from other countries in the study of BIM-supported project performance. Secondly, this study also proposes multiple stages of BIM application and multiple dimensions of project performance. Researchers from other countries can consider the five BIM conditions according to their own country's stage of BIM application development. These findings are also inspiring for researchers when exploring related issues. Thirdly, the results indicate the nonlinear relationship between BIM and performance, meaning that BIM does not always lead to improved project performance. Policymakers in other countries should take into full account the five BIM conditions during the process of promoting BIM applications.

Practical contribution

The findings facilitate project stakeholders in gaining a deeper understanding of the significance of BIM application in improving project performance, which holds substantial practical significance. Combined with the actual application stage of BIM, the actual project objectives, and their own needs, different stakeholders can refer to the performance improvement paths to utilize BIM conditions to enhance either the comprehensive performance or the individual performance of the civil engineering project.

- In the embryonic stage: to reduce project cost, managers should ensure personnel with adequate BIM knowledge, and skills by carrying out BIM and 3D modeling training; to accelerate the project schedule, practitioners should emphasize the use of Industry Foundation Classes IFC-based file conversion and data management, promote the localization of BIM platform and software compatibility, and added BIM application

points; to improve project's quality and comprehensive performance, practitioners should improve BIM team building by signing multi-party contracts to make sure the members can be effectively integrated in a team.
- In the development stage: to accelerate the project schedule, BIM standards need to be defined and set to guide the project management team in making project-related decisions; to improve project quality, more BIM application points are needed to promote the BIM application degree, which will produce better quality control effect on the project; to improve comprehensive performance, active promotion of the BIM team building and more BIM application points are needed to achieve better control across the life cycle.
- In the stability stage: to accelerate the project schedule, practitioners should promote BIM team building through high-quality interactions to reduce construction delays; to improve project quality, the appropriate BIM application platform, the standards for BIM quality management, and more BIM application points are needed for the improvement of quality control effect; to improve comprehensive performance, practitioners should focus on BIM team building and BIM application points.
- In the maturity stage: to accelerate the project schedule, practitioners should improve their familiarity with the use of more BIM applications and the definition of specific control points; to reduce project cost and improve comprehensive performance, practitioners should establish the information interaction platform and improve BIM standard system by combining BIM with smart site standards, and more BIM application points are needed at the same time.

Limitations and prospects
Finally, this work still has few limitations and prospects: (1) This research examines the civil engineering project cases using BIM technology within the context of China's AEC industry. Given the differences in the level of development and the application of BIM technology, future research needs to extend to project case studies in different national or regional contexts, such as high-level BIM application countries like the United States, medium-level BIM application countries like South Korea, and low-level BIM application countries like India; (2) This research only considers civil engineering projects' comprehensive performance involving cost, schedule, quality. Thus, future research can make the comprehensive performance of civil engineering projects cover more fields and parameters, such as project safety indicators; (3) The research is based on Chinese cases, which have the same external environmental factors. Future research will consider the impact of external environmental factors such as policy support and market maturity in different countries.

Data availability
Data are contained within the article and its supplementary information files.

Received: 2 March 2025; Accepted: 10 June 2025
Published online: 02 July 2025

References
1. Sarvari, H., Chan, D. W., Rakhshanifar, M., Banaitiene, N. & Banaitis, A. Evaluating the impact of building information modeling (BIM) on mass house building projects. *Buildings* **10**, 35 (2020).
2. Zhou, D., Pei, B., Li, X., Jiang, D. & Wen, L. Innovative BIM technology application in the construction management of highway. *Sci. Rep.* **14**, 15298 (2024).
3. Abbasnejad, B., Nepal, M. P., Ahankoob, A., Nasirian, A. & Drogemuller, R. Building information modelling (BIM) adoption and implementation enablers in AEC firms: A systematic literature review. *Archit. Eng. Des. Manag.* **17**, 411–433 (2021).
4. Hu, X., Guo, X. & Chen, Y. in *Construction Research Congress*, 711–721 (2024).
5. Nabil, Y., Ibrahim, A. H. & Hosny, S. Practices improvement of building information modeling in the Egyptian construction projects. *Sci. Rep.* **14**, 13536 (2024).
6. Soh, M. F., Bigras, D., Barbeau, D., Doré, S. & Forgues, D. BIM machine learning and design rules to improve the assembly time in steel construction projects. *Sustainability* **14**, 288 (2021).
7. Wang, L., Lee, J., Nimawat, J., Han, K. & Gupta, A. Integrated 4D design change management model for construction projects. *J. Constr. Eng. Manag.* **150**, 04024023 (2024).
8. Li, J., Li, N., Peng, J., Cui, H. & Wu, Z. A review of currently applied building information modeling tools of constructions in China. *J. Clean. Prod.* **201**, 358–368 (2018).
9. Wang, Q. et al. BIM voxelization method supporting cell-based creation of a path-planning environment. *J. Constr. Eng. Manag.* **146**, 04020080 (2020).
10. Liu, N., Guo, D., Song, Z., Zhong, S. & Hu, R. BIM-based digital platform and risk management system for mountain tunnel construction. *Sci. Rep.* **13**, 7585 (2023).
11. Sabet, P. G. P. & Chong, H.-Y. Interactions between building information modelling and off-site manufacturing for productivity improvement. *Int. J. Manag. Proj. Bus.* **13**, 233–255 (2019).
12. Abanda, F. H., Vidalakis, C., Oti, A. H. & Tah, J. H. A critical analysis of building information modelling systems used in construction projects. *Adv. Eng. Softw.* **90**, 183–201 (2015).
13. Luong, D. L., Truong, N.-S., Ngo, N.-T. & Nguyen, N.-Q. Developing the hybrid BIM–BEM and jellyfish search optimization system for optimizing energy consumption and building installation costs. *Sci. Rep.* **14**, 17186 (2024).
14. Guo, Z. et al. Reducing redundancy in large MEP building information models for facility management using oriented bounding boxes and hash sets. *Autom. Constr.* **165**, 105514 (2024).
15. Franz, B. & Messner, J. Evaluating the impact of building information modeling on project performance. *J. Comput. Civ. Eng.* **33**, 04019015 (2019).
16. Celoza, A., Leite, F. & de Oliveira, D. P. Impact of BIM-related contract factors on project performance. *J. Leg. Aff. Disput. Resolut. Eng. Constr.* **13**, 04521011 (2021).
17. Su, G. & Khallaf, R. Research on the influence of risk on construction project performance: A systematic review. *Sustainability* **14**, 6412 (2022).
18. Zoghi, M., Lee, D. & Kim, S. A computational simulation model for assessing social performance of BIM implementations in construction projects. *J. Comput. Des. Eng.* **8**, 799–811 (2021).
19. Poirier, E. A., Staub-French, S. & Forgues, D. Assessing the performance of the building information modeling (BIM) implementation process within a small specialty contracting enterprise. *Can. J. Civ. Eng.* **42**, 766–778 (2015).

20. Luo, L., Chen, H., Yang, Y., Wu, G. & Chen, L. A three-stage network DEA approach for performance evaluation of BIM application in construction projects. *Technol. Soc.* **71**, 102105 (2022).
21. Jiang, H.-J., Cui, Z.-P., Yin, H. & Yang, Z.-B. BIM performance, project complexity, and user satisfaction: A QCA study of 39 cases. *Adv. Civ. Eng.* **2021**, 6654851 (2021).
22. Li, J., Yang, M., Liu, C., Li, A. & Guo, B. Listen to the companies: Exploring BIM job competency requirements by text mining of recruitment information in China. *J. Constr. Eng. Manag.* **149**, 04023076 (2023).
23. Lu, W., Xu, J. & Söderlund, J. Exploring the effects of building information modeling on projects: Longitudinal social network analysis. *J. Constr. Eng. Manag.* **146**, 04020037 (2020).
24. Zhang, H. M., Chong, H.-Y., Zeng, Y. & Zhang, W. The effective mediating role of stakeholder management in the relationship between BIM implementation and project performance. *Eng. Constr. Archit. Manag.* **30**, 2503–2522 (2022).
25. Mellado, F., Lou, E. C. & Becerra, C. L. C. Synthesising performance in the construction industry: An analysis of performance indicators to promote project improvement. *Eng. Constr. Archit. Manag.* **27**, 579–608 (2019).
26. Gaur, S. & Tawalare, A. Investigating the role of BIM in stakeholder management: Evidence from a metro-rail project. *J. Manag. Eng.* **38**, 05021013 (2022).
27. Suprun, E. et al. Digitisation of existing water facilities: A framework for realising the value of scan-to-BIM. *Sustainability* **14**, 6142 (2022).
28. Wu, W., Ren, C., Wang, Y., Liu, T. & Li, L. DEA-based performance evaluation system for construction enterprises based on BIM technology. *J. Comput. Civ. Eng.* **32**, 04017081 (2018).
29. Abou-Ibrahim, H. & Hamzeh, F. Understanding stakeholders' impact on design workflow dynamics using agent-based modeling. *Autom. Constr.* **138**, 104254 (2022).
30. Ganbat, T., Chong, H.-Y., Liao, P.-C. & Lee, C.-Y. A cross-systematic review of addressing risks in building information modelling-enabled international construction projects. *Arch. Comput. Methods Eng.* **26**, 899–931 (2019).
31. Fischer, M., Ashcraft, H. W., Reed, D. & Khanzode, A. *Integrating Project Delivery* (Wiley, 2017).
32. Hwang, B. G., Shan, M. & Looi, K. Y. Key constraints and mitigation strategies for prefabricated prefinished volumetric construction. *J. Clean. Prod.* **183**, 183–193 (2018).
33. Bouras, A., Eynard, B., Foufou, S. & Thoben, K.-D. *Product Lifecycle Management in the Era of Internet of Things: 12th IFIP WG 5.1 International Conference, PLM 2015, Doha, Qatar, October 19–21, 2015, Revised Selected Papers*, vol. 467 (Springer, 2016).
34. Saka, A. B. & Chan, D. W. Knowledge, skills and functionalities requirements for quantity surveyors in building information modelling (BIM) work environment: an international Delphi study. *Archit. Eng. Des. Manag.* **16**, 227–246 (2020).
35. Meng, G., Hu, H. & Chen, L. The application obstacles of BIM technology in green building project and its key role path analysis. *Sci. Rep.* **14**, 30330 (2024).
36. Zhang, S. et al. Optimization of architectural design and construction with integrated BIM and PLM methodologies. *Sci. Rep.* **14**, 26153 (2024).
37. Dakhil, A., Underwood, J. & Alshawi, M. Critical success competencies for the BIM implementation process: UK construction clients. *J. Inf. Technol. Constr. (ITcon)* **24**, 80–94 (2019).
38. Messner, J. I., Anumba, C., Dubler, C., Goodman, S. & Zikic, N. *BIM Project Execution Planning Guide* (2011).
39. Hong, Y., Hammad, A. W., Sepasgozar, S. & Akbarnezhad, A. BIM adoption model for small and medium construction organisations in Australia. *Eng. Constr. Archit. Manag.* **26**, 154–183 (2018).
40. Lee, C.-Y. & Chong, H.-Y. Influence of prior ties on trust and contract functions for BIM-enabled EPC megaproject performance. *J. Constr. Eng. Manag.* **147**, 04021057 (2021).
41. Wang, K., Zhang, C., Guo, F. & Guo, S. Toward an efficient construction process: What drives BIM professionals to collaborate in BIM-enabled projects. *J. Manag. Eng.* **38**, 04022033 (2022).
42. Li, Q., Chong, H.-Y., Lee, C.-Y. & Zhang, Y. BIM's formal and informal collaborative networks in traditional procurement: Insights from the construction phase of a hospital case study. *J. Manag. Eng.* **37**, 05021008 (2021).
43. Ham, N., Moon, S., Kim, J.-H. & Kim, J.-J. Optimal BIM staffing in construction projects using a queueing model. *Autom. Constr.* **113**, 103123 (2020).
44. Barqawi, M., Chong, H.-Y. & Jonescu, E. A review of employer-caused delay factors in traditional and building information modeling (BIM)-enabled projects: Research framework. *Adv. Civ. Eng.* **2021**, 6696203 (2021).
45. Sun, C., Xu, H. & Jiang, S. Understanding the risk factors of BIM technology implementation in the construction industry: An interpretive structural modeling (ISM) approach. *Eng. Constr. Archit. Manag.* **27**, 3289–3308 (2020).
46. Ozturk, G. B. Interoperability in building information modeling for AECO/FM industry. *Autom. Constr.* **113**, 103122 (2020).
47. Tan, T., Chen, K., Xue, F. & Lu, W. Barriers to building information modeling (BIM) implementation in China's prefabricated construction: An interpretive structural modeling (ISM) approach. *J. Clean. Prod.* **219**, 949–959 (2019).
48. Bedford, D. S. & Sandelin, M. Investigating management control configurations using qualitative comparative analysis: An overview and guidelines for application. *J. Manag. Control* **26**, 5–26 (2015).
49. Cho, K., Ahn, S., Park, K. & Kim, T. W. Schedule delay leading indicators in precast concrete construction projects: Qualitative comparative analysis of Korean cases. *J. Manag. Eng.* **37**, 04021024 (2021).
50. Rihoux, B. & Ragin, C. C. *Configurational Comparative Methods: Qualitative Comparative Analysis (QCA) and Related Techniques* (Sage Publications, 2008).
51. Pappas, I. O. & Woodside, A. G. Fuzzy-set qualitative comparative analysis (fsQCA): Guidelines for research practice in Information Systems and marketing. *Int. J. Inf. Manag.* **58**, 102310 (2021).
52. Feng, L., Liu, J., Wang, Z. & Hong, Y. Navigating compliance complexity: Insights from the MOA framework in international construction. *Eng. Constr. Archit. Manag.* https://doi.org/10.1108/ECAM-02-2024-0163 (2024).
53. Li, Y., Zhang, Y., Li, Y. & Ding, R. Exploring the impact of dynamic capabilities on the sustainable delivery of international engineering projects: A configurational approach. *IEEE Trans. Eng. Manag.* **71**, 9003–9018. https://doi.org/10.1109/TEM.2023.3330650 (2024).
54. Wang, Y., Xu, J., Liu, J. & Li, Y. Turning pressure into power: The configuration effect of antecedents on the digital transformation of engineering enterprises. *J. Manag. Eng.* **40**, 04023059. https://doi.org/10.1061/JMENEA.MEENG-5636 (2024).
55. Xu, C., Chen, Y., Yao, H. & Zhang, L. The opportunism-inhibiting effects of the alignment between engineering project characteristics and contractual governance: Paired data from contract text mining and survey. *IEEE Trans. Eng. Manag.* **71**, 15110–15124. https://doi.org/10.1109/TEM.2024.3480254 (2024).
56. Dang, X., Peng, J. & Deng, X. How to improve the environmental, social and governance performance of Chinese construction enterprises based on the fuzzy set qualitative comparative analysis method. *Sustainability* **16**, 3153 (2024).
57. Ma, T. & Liu, Y. Multiple paths to enhancing the resilience of project-based organizations from the perspective of CSR configuration: evidence from the Chinese construction industry. *Eng. Constr. Archit. Manag.* **31**, 835–865. https://doi.org/10.1108/ECAM-06-2022-0526 (2024).
58. Ma, L. & Fu, H. Exploring the influence of project complexity on the mega construction project success: a qualitative comparative analysis (QCA) method. *Eng. Constr. Archit. Manag.* **27**, 2429–2449 (2020).
59. Kou, Y. & Liu, K. Optimization path for construction safety resilience in megaprojects from the perspective of configuration. *Int. J. Occup. Saf. Ergon.* **31**, 1–12 (2025).
60. Wu, Q., Bo, Q., Luo, L., Yang, C. & Wang, J. Influencing factors and governance strategies of megaproject complexity based on fuzzy-set qualitative comparative analysis. *Eng. Constr. Archit. Manag.* **31**, 3533–3556. https://doi.org/10.1108/ECAM-12-2022-1203 (2024).

61. Montalbán-Domingo, L., Casas-Rico, J., Alarcón, L. F. & Pellicer, E. Influence of the experience of the project manager and the foreman on project management's success in the context of LPS implementation. *Ain Shams Eng. J.* **15**, 102324. https://doi.org/10.1016/j.asej.2023.102324 (2024).
62. Berg-Schlosser, D. & Meur, G. *Comparative Research Design: Case and Variable Selection*, 19–32 (2009).
63. Ragin, C. C. Fuzzy sets: Calibration versus measurement. In *Methodology Oxford handbooks of Political Science*, vol. 2 (2007).
64. Skaaning, S.-E. Assessing the robustness of crisp-set and fuzzy-set QCA results. *Sociol. Methods Res.* **40**, 391–408 (2011).
65. Bell, R. G., Filatotchev, I. & Aguilera, R. V. Corporate governance and investors' perceptions of foreign IPO value: An institutional perspective. *Acad. Manag. J.* **57**, 301–320 (2014).
66. Du, Y. & Kim, P. H. One size does not fit all: Strategy configurations, complex environments, and new venture performance in emerging economies—ScienceDirect. *J. Bus. Res.* **124**, 272–285 (2021).
67. Fiss, P. C. Building better causal theories: A fuzzy set approach to typologies in organization research. *Acad. Manag. J.* **54**, 393–420 (2011).
68. Schneider, C. Q. & Wagemann, C. *Set-Theoretic Methods for the Social Sciences: A Guide to Qualitative Comparative Analysis* (Cambridge University Press, 2012).
69. Dwivedi, P., Joshi, A. & Misangyi, V. F. Gender-inclusive Gatekeeping: How (mostly male) predecessors influence the success of female CEOs. *Acad. Manag. J.* **61**, 379–404. https://doi.org/10.5465/amj.2015.1238 (2018).
70. Cheng, J., Luo, J., Du, Y. & Liu, Q. What kinds of entrepreneurial ecosystem can produce country-level female high entrepreneurial activity. *Stud. Sci. Sci.* **39**, 695–702 (2021).
71. Mayer, P., Funtík, T., Erdélyi, J., Honti, R. & Cerovšek, T. Assessing the duration of the lead appointed party coordination tasks and evaluating the appropriate team composition on BIM projects. *Buildings* **11**, 664 (2021).
72. Jo, C. & Choi, J. BIM information standard framework for model integration and utilization based on openBIM. *Appl. Sci.* **11**, 9926 (2021).
73. Kwon, O. C. & Jo, C. W. Proposal of BIM quality management standard by analyzing domestic and international BIM guides. *J. Korea Inst. Build. Constr.* **11**, 265–275 (2011).
74. Qiao, Y. *Construction Project Vertical Governance Based on BIM* (Xi 'an University of Architecture and Technology, 2017).
75. Hyarat, E., Hyarat, T. & Al Kuisi, M. Barriers to the Implementation of building information modeling among Jordanian AEC companies. *Buildings* **12**, 150 (2022).
76. Asim, J., Ahmed, R., Streimikiene, D., Rasheed, S. & Streimikis, J. Assessing design information quality in the construction industry: Evidence from building information modeling. *Acta Montan. Slovaca* **26**, 235–251. https://doi.org/10.46544/AMS.v26i2.05 (2021).
77. Radujković, M., Sjekavica Klepo, M. & Bosch-Rekveldt, M. Breakdown of engineering projects' success criteria. *J. Constr. Eng. Manag.* **147**, 04021144 (2021).
78. Chen, S. et al. Potential features of building information modelling for application of project management knowledge areas as advances modeling tools. *Adv. Eng. Softw.* **176**, 103372. https://doi.org/10.1016/j.advengsoft.2022.103372 (2023).
79. Mat Ya'acob, I. A., Mohd Rahim, F. A. & Zainon, N. Risk in implementing building information modelling (BIM) in Malaysia construction industry: A review. *E3S Web Conf.* **65**, 03002 (2018).
80. Isaac, S. & Shimanovich, M. Automated scheduling and control of mechanical and electrical works with BIM. *Autom. Constr.* **124**, 103600 (2021).
81. Lin, Y.-C. & Yang, H.-H. A framework for collaboration management of BIM model creation in architectural projects. *J. Asian Archit. Build. Eng.* **17**, 39–46. https://doi.org/10.3130/jaabe.17.39 (2018).
82. Cao, Y., Kamaruzzaman, S. N. & Aziz, N. M. Green building construction: A systematic review of BIM utilization. *Buildings* **12**, 1205 (2022).
83. Hwang, B.-G., Zhao, X. & Yang, K. W. Effect of BIM on rework in construction projects in Singapore: Status quo, magnitude, impact, and strategies. *J. Constr. Eng. Manag.* **145**, 04018125 (2019).
84. Shin, J., Ju, K.-B., Son, A.-Y. & Moon, H.-S. A study on the BIM platform required functions and application for road and river construction project management. *J. Korean Inst. Commun. Inf. Sci.* **45**, 1893–1906 (2020).
85. Chan, D. W. M., Olawumi, T. O. & Ho, A. M. L. Perceived benefits of and barriers to building information modelling (BIM) implementation in construction: The case of Hong Kong. *J. Build. Eng.* **25**, 100764 (2019).

Acknowledgements
This work was supported by the Doctors' Research Startup Fund of Hubei University of Technology [XJ2022010801], and the 2021 Hubei Province Construction Science and Technology Plan Project.

Author contributions
W.Z.: Conceptualization, Methodology, Supervision and Funding, T.M.: data collection, writing review and editing; X.J.: investigation, data collection; S.Z. and N.Y.: Methodology, Software, and original draft. All authors reviewed the manuscript.

Declarations

Competing interests
The authors declare no competing interests.

Additional information
Supplementary Information The online version contains supplementary material available at https://doi.org/10.1038/s41598-025-06662-x.

Correspondence and requests for materials should be addressed to W.Z. or T.M.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.