



Influence on BIM project performance at project life-cycle stages: A network perspective

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Abstract

It has been extensively shown that Building Information Modelling (BIM) improves project performance, which is impacted by various critical performance factors of BIM project (CPFs-BP). However, it has become a difficult problem in theory and practice to determine the most important CPFs-BP impacting BIM project performance (BPP) at various life-cycle stages. In light of this information gap, the goal of this study is to identify the most important CPFs-BP and identify the stages at which BIM can be applied to enhance BPP through specific CPFs-BP. Using a review of the literature, this work first discovers and characterizes 17 CPFs-BP. Then, by constructing a two-dimensional, two-mode network of heterogeneous nodes, this study demonstrates the top seven CPFs-BP, the relationship between CPFs-BP and life-cycle stages, and the relative significance of various life-cycle stages in BIM projects using descriptive methods and complex network theory. BPP prediction models were then constructed and validated utilizing fitness parameters using MATLAB and data obtained from expert interviews and surveys. Lastly, five specific strategies are put forth to enhance BPP: increasing BIM accuracy during the construction phase, enhancing stakeholders' capacity to coordinate the design of construction documents, enhancing BIM accuracy during the completion phase, fostering cooperation between conceptual design organizations, and utilizing the BIM system environment during the construction phase. Important BIM project stakeholders can apply the study's conclusions. Finally, five specific approaches to improving BPP are proposed: improving BIM accuracy at the construction stage, stakeholders' ability to organize construction document design, BIM accuracy at the completion stage, collaboration between conceptual design organizations, and the BIM system environment during the construction stage. The study is useful for key stakeholders in BIM projects who can put its findings into practice and help evaluate BPP throughout the project's life cycle.

Keywords: Building information modelling, BIM project performance, critical performance factors of BIM project, life-cycle stages, improvement strategies

1. Introduction

Low productivity and efficiency have become typical throughout the building project lifecycle^[1]. Building information modelling (BIM) has emerged as a potential approach for creating realistic virtual models and supporting project operations throughout the project's lifecycle^[2,3]. BIM, a digital technology that allows for the creation of accurate virtual models and supports additional activities in the project delivery process^[2], is a digital representation used to plan, design, control, and maintain facilities. It has changed the traditional ways that project participants define their roles^[4] and collaborate, and it has enabled teams to manage projects using a model-based cooperative approach^[5]. BIM improves BIM project performance (BPP) in the following ways: cost savings and high returns^[6], faster delivery^[7], safety, higher quality^[8], fewer document errors and rework^[9], perceived facility quality, and better decision-making^[10]. However, the extent to which BIM improves project performance varies greatly between projects, frequently due to variances in implementation, stakeholder engagement, or organizational norms.

While BIM has been demonstrated to improve project performance, it can also have a negative influence on BPP, such as increased in-construction requests for information (RFIs), increased change order costs, and increased punch list expenses^[11], among other things. Worse, BPP is linked to certain project stakeholders and stages. For example, a failure to uncover design mistakes and RFIs prior to construction may be due to an overreliance on BIM software and insufficient cooperation between suppliers and designers^[11,12]. The implementation of BIM technology at various phases has a significant impact on BPP, particularly due to the BIM interoperability issue and the functionality of BIM tools^[13]. Therefore, it is necessary to examine critical performance factors of BIM



project (CPFs-BP) in terms of various aspects: (1) BIM technology^[14], (2) stakeholder competitiveness^[15,16] and stakeholder interaction^[1], and (3) project stages.

BPP originates from the dynamic interaction of these CPFs-BP. Owners, contractors, designers, and BIM consultants all use BIM differently depending on their goals and roles, and project stages influence the impact of these actions. Owners want to finish a project within a particular timetable, budget, and specifications^[5]. They recognize the significant potential advantage of employing BIM technology^[17], since they may benefit the most from using a facility model and its inherent knowledge of the facility’s lifecycle^[18]. Contractors aim to make the highest possible profit from the project^[5] and consider themselves as the party that benefitted most from BIM technology^[6], as they perceive the top project benefits of BIM to be reduced errors and omissions, collaboration with owners and design firms, reduced rework, reduced construction cost, better cost control and predictability, and reduced overall project duration^[19]. Designers use BIM to reduce document errors, improve workflows, and support coordination during construction^[20]. Designers consider the reduction in design revisions to be the most significant benefit of BIM^[6]. Although owners recognize the high potential value of using BIM, many are unsure about which stage of BPP to improve over the lifecycle^[21]. Understanding how CPFs and BPP interact is therefore critical for increasing BIM utilization and project outcomes across the lifecycle.

Recent studies have investigated BPP using a variety of approaches, but no study has developed a phase-based approach to predict and improve BPP considering multiple CPFs-BP. Besides, few quantitative studies have attempted to clarify the complex relationships between the project stages and CPFs-BP. Therefore, this study answers two research questions: 1) At what point in the project lifecycle might the use of BIM technology increase BPP? 2) How to increase BPP? To fill a research need, this study will identify CPFs-BP and build a two-mode network model between CPFs-BP and eight project stages in a project lifetime. This study will assist the primary stakeholders in BIM projects in improving their BPP based on current circumstances.

To accomplish this, a complex network technique is used to describe CPFs-BP as interconnected nodes, allowing for systematic and quantitative identification of significant elements and interaction analysis. By taking this approach, the study not only broadens our understanding of how CPFs and BP interact to affect BPP, but it also offers project managers actionable insights to optimize BIM deployment and project outcomes. In doing so, the study adds to both the academic literature on BIM performance and the practical decision-making process in building project management.

2. Literature Review

2.1 BPP

BPP can encompass several critical items such as cost, rework, project schedule, stakeholder satisfaction, facility management, etc^[7,11]. Some research has focused on BPP at the inter-organization level^[22], intra-organization level, project level, and individual level^[23]. Other studies investigated BPP at the country level. For example, Hu and Chen^[11] discovered a difference in BPP based on 12 variables between nations that included and excluded the United States; Van Tam *et al.*^[24] discovered that BIM technology-related factors had a substantial influence on BPP in developing countries. Moreover, BPP relies on the application of BIM technology at different life-cycle stages, such as field data analysis and scheme comparison in the project proposal stage, 3D space integration in the feasibility study^[25] and visual design/collision detection in the concept design stage^[26]. However, few studies have addressed how to improve BPP using various CPFs-BP at the life-cycle stage level, and most stakeholders are still unsure about how, when, and where to adopt BIM^[21].

As shown in Table 1, a list of 17 CPFs-BP and their explanations are given based on an extensive literature review, and they are classified into three groups: BIM technology (CPFs-BP1–8), stakeholder competitiveness (CPFs-BP9–12), and stakeholder interaction (CPFs-BP13–17). Nonetheless, few studies have considered how BIM adoption might improve project performance by precisely controlling a series of key factors. Therefore, one of the research objectives is to determine the principal CPFs-BP in accordance with Table 1.

Table 1. Description of CPFs-BP.

CPFs-BP	Description
Functionality of BIM tools (CPFs-BP1)	It is essential to confirm what BIM tools need to be adopted to help deliver expected BIM uses ^[14] . Despite the software vendor’s claim of access to wonderful functions, the usability of new advanced technology is subject to how users define and implement it in practice ^[13] .
Compatibility of BIM tools (CPFs-BP2)	It measures the convenience and evaluates the received outcomes or products when people adopt different tools and standards resulting in different model formats and levels of details ^[4] . In addition, interoperability problems between BIM models and other project management software packages, as well as those among various engineering information, still trouble practitioners ^[27-29] .

Diversity of BIM application areas (CPFs-BP3)	BIM uses include five generic categories: (1) architectural design, engineering system design, (2) MEP coordination/conflict detection, (3) two-dimensional (2D) documentation, three-dimensional (3D) detailing, and four-dimensional (4D) scheduling, and (4) facility management ^[20] . Other areas such as BIM/GIS overlapping, energy simulation, and sustainability analysis are also influential on project objectives ^[14] .
BIM quality (CPFs-BP4)	It refers to how well a BIM model fulfils the requirements. Liu <i>et al.</i> ^[13] offered some detailed metrics, including the ratio of the warnings to objects, criticality of warnings, consistency of 3D model and 2D references, and analytical reporting quality (the structural analysis quality, daylighting simulation report quality, energy simulation report quality, etc.).
BIM accuracy (CPFs-BP5)	It refers to how precisely the BIM model reflects the physical conditions of projects, i.e., how closely the BIM's geometry/data represents as-built conditions in the field. Quantity takeoff accuracy, discrepancies between models, average number of generic objects per assembly, and constructability, can jointly depict BIM accuracy ^[4] .
BIM usefulness (CPFs-BP6)	It refers to how useful the model information and geometry is over the project lifecycle. Some variables might be how often the model is accessed for different purposes, ease of construction documentation creation, and reliability of model data for end-user during operation and maintenance ^[4] .
BIM economy (CPFs-BP7)	It refers to whether it is constructed in the most cost and time-efficient manner, which is also related to how fast a BIM is developed on average ^[4] . It may involve a high initial investment in BIM projects ^[30] , expensive cost for design changes, and financial support for infrastructure ^[29,31] .
BIM Institutional Environment (CPFs-BP8)	It refers to the regulatory system formed by BIM-related standards and technical requirements, organizational rules and requirements, and policy and legal issues to ensure BIM implementation within the project context ^[32] . An institutional environment within a BIM-based project is required to facilitate BIM governance and ensure collaborative working among project teams ^[32] .
Capability of stakeholders' organizations (CPFs-BP9)	It includes competency of individual stakeholders, capability and maturity of AECO organizations, maturity of using BIM technology and workflows ^[6] . Lack of BIM knowledge in the team members is to the disadvantage of BIM adoption ^[33] .
Stakeholders' roles and responsibilities (CPFs-BP10)	The best practices of BIM include clear roles and responsibilities in BIM affairs within the coordination process ^[15,16] .
Organizations' adaptability to changes (CPFs-BP11)	Different organizations should develop adaptability to changes, which enables participants to fit in the exchange environment quickly and obtain mutual benefits, and then improve their overall performance ^[1] .
Inter-organization leadership (CPFs-BP12)	It refers to the relative leadership between project stakeholders and leaders can complete the work collaboratively, rather than solely face the challenges of restructuring projects organizationally ^[4] . For example, when design errors occur in the clash detection, or the unreasonable schedule is discovered in the visualization room, it is hard to be corrected because of the ambiguous power relationship ^[13] .
Stakeholders' involvement (CPFs-BP13)	It emphasizes to what degree and how much time the stakeholders are involved in delivering BIM uses ^[14,34] . It is critical in BEP for successful BIM implementation ^[35] .
Contract (CPFs-BP14)	A correct and matching contract should be constructed because proper contract management will positively influence project performance ^[16] . It works as a measure to improve BIM collaboration and reduce subsequent disputes ^[36] .
Inter-organizational trust (CPFs-BP15)	A firm expects that its partner will not behave opportunistically and allows firms to exchange information and share responsibilities for decision making ^[29] . Trust relationships inspire the diffusion of valuable knowledge and innovations, which lessens opportunism and contributes to project performance ^[37] .

Inter-organization communication (CPFs-BP16)	It facilitates different organizations from different backgrounds to exchange knowledge and frequently ^[1] . Consequently, project players can amplify their efforts. Positive behaviours can improve project performance, such as resolving problems collaboratively, working harmoniously, and engaging in mutual support ^[7,11,36] .
Information exchange (CPFs-BP17)	Frequent information exchange is the basic element of cooperation and shows more effects on project performance due to the enormous information applied to BIM models ^[1] .

CPFs-BP: critical performance factors of BIM project; BIM: Building Information Modelling; MEP: mechanical, electrical, and plumbing; AECO: architecture, engineering, construction, and operation; BEP: BIM Execution Planning.

2.2 Methods of BPP research

Diverse qualitative and quantitative methodologies have been used to investigate the influence and optimization mechanisms of BPP. Qualitative analysis includes surveys^[16], interviews^[38], contract-based models^[37], and so on. Celozza *et al.*^[16] surveyed the industry on BIM practices and evaluated the impact of BIM-related contract practices on project performance; Chen *et al.*^[38] conducted qualitative interviews to understand how the performance indicators are influenced by the use of BIM; and Lee *et al.*^[37] proposed an integrative trust-based functional contracting model that describes how trust can enhance BPP in engineering, procurement.

Other methods aim to quantify the relation between BIM implementation and project performance, such as the partial least squares structural equation modelling^[5], dynamic model^[39], benchmarking models^[13,40,41], and Bayesian network models^[42]. Tang *et al.*^[1] explored the direct relationship between BIM implementation and the performance of off-site manufacturing projects using the partial least-squares structural equation modelling; by the same technique, Lee *et al.*^[5] analyzed joint contract-function effects on BIM-enabled EPC project performance; Zoghi *et al.*^[39] developed a system dynamics model to evaluate the social performance of BIM-integrated construction management; and Chen and Liu^[42] used a Bayesian belief network to solve the innovation performance problems of a BIM innovation project in China. Although these methods are useful for revealing the influence of CPFs-BP on BPP, few methods have considered that BPP is prone to change during a long project period, and the point is how to illustrate the relationship between CPFs-BP and project stages.

2.3 Complex network theory

To address the relationship between CPFs-BP and project stages, complex network theory is applied in this study, which is a research paradigm for modeling and visualizing diverse complex systems. On the one hand, a complex network can evolve over time and space and can undergo change. Typically, nodes or connecting edges can be added or removed to alter the network structure. It is possible to abstract the connection between various project stages and CPFs-BP into a complicated network. On the other hand, it has been challenging to investigate large-scale network interactions using mathematical analytic techniques, including the “network” at various stages of the project and the “network” between CPFs-BP. However, the complex network theory derived from graph theory can address this issue. Complex network analysis is more appropriate than other methods in this study because it has a tendency to solve the issues, such as comparing the state of constituent parts, forming alliances between constituent elements, and information sharing and transfer among constituent elements.

Complex network theory is thus applied by visualizing the relation as an intuitive 2-mode network. Moreover, the theory has been widely used in identifying critical factors and quantifying relations between homogeneous or heterogeneous nodes. A single type of node (e.g., people, risks) can form a 1-mode network, such as the study in He *et al.*^[43], which is the current research focus. Two types of nodes can constitute a 2-mode network (also known as bipartite network)^[44], such as the study in Wu *et al.*^[45], where no direct link exists between homogeneous nodes. Among all parameters, maximum matching is one algorithm particularly used to deal with real-world problems by matching heterogeneous nodes (e.g., buyers and sellers) in bipartite networks^[46]. Network analysis is useful to present and measure the internal and external relationships between CPFs-BP and project stages. However, it is far from enough to predict and optimize project performance by only relying on the two-dimensional relation^[37,47].

The current BPP research mainly focuses on the evaluation of BPP, and the methods used are mainly statistical methods or system theory based on causality^[48]. However, in fact, a concept of “interaction” has been produced in the process of researching the phased performance of BIM projects, which is difficult to research using quantitative analysis tools^[49]. Few studies have used complex network theory to improve BPP at life-cycle stages. Complex network analysis could be used to solve problems such as comparing constituent element status, forming alliances among constituent elements, and transmitting and sharing information among constituent parts. As a result, developing an all-stage BPP relationship research model based on the network method may address the bottleneck in effective prediction and improvement of BPP in practice. Compared with existing evaluation frameworks, such as structural equation modeling (SEM) and Bayesian networks, the proposed network-polynomial approach offers complementary strengths. SEM mainly models linear and predefined causal relationships, while Bayesian networks rely on prior probability assumptions. In contrast, complex-network analysis captures multi-directional interactions among CPFs-BP, and polynomial functions allow for nonlinear stage-based prediction of BPP. Together, this approach provides a flexible way to explore dynamic relationships across life-cycle stages.

In this study, complex network analysis is used to address specific challenges in BPP, such as quantifying interactions between CPFs-BP and project stages, identifying key factors and their interdependencies, and supporting dynamic, lifecycle-wide evaluation and optimization of BPP.

3. Methodology

To ensure that the identification of CPFs-BP was systematic and replicable, a content analysis approach was adopted. Firstly, 30 peer-reviewed journal papers published between 2013 and 2024 were collected from Scopus, Web of Science, and Engineering Village using the keywords “BIM performance”, “BIM factors”, “project performance”, and “BIM adoption”. Second, all BIM-related factors associated with project performance outcomes were retrieved. Through open coding and factor clustering, repeated or synonymous factors were merged, resulting in a consolidated list of 17 unique CPFs-BP. These factors were then grouped into three dimensions—BIM technology, stakeholder competitiveness, and stakeholder interaction—in accordance with existing BIM performance frameworks^[6]. To further validate completeness, three industry experts (two BIM managers and one digital consultant, each with over ten years of AEC experience) were invited to assess the relevance of each factor. Only the factors rated as important by all experts were retained. The final set of 17 CPFs-BP is presented in [Table 1](#), forming the initial input for the subsequent complex network modelling. Finally, 17 CPFs-BP with a frequency higher than five were used in this study, with the list of CPFs-BP occurrence frequencies from the literature review as shown in [Table 2](#).

Only factors that occurred more than five times in the literature were kept from the original list of thirty to guarantee that the chosen CPFs-BP were well-known, pertinent, and significant for further study. This frequency-based threshold was selected to minimize the inclusion of infrequently reported or marginally significant features while striking a balance between comprehensiveness and practical usefulness. As a result, the final set of 17 CPFs-BP offers a solid, representative, and trustworthy basis for the ensuing complicated network modelling, assessment, and identification of critical elements affecting BPP throughout various life-cycle stages.

Then, combining descriptive analysis and complex network theory, the top seven CPFs-BP among the 17 were identified, and the relationship between project stages and CPFs-BP was discovered using literature review and data collected from Survey I. Survey I was designed to identify the most influential CPFs-BP and explore their interactions with different project life-cycle stages. Following that, by analysing the parameters of the established two-dimensional two-mode heterogeneous network model, this study explained the interaction between CPFs-BP and life-cycle stages. Subsequently, Survey II was used to evaluate the top seven CPFs-BP along with network analysis. Survey II aimed to evaluate the impact of these top seven CPFs-BP on BPP and predict improvement strategies by quantifying their contributions at each project stage. Finally, a total of 56 BPP evaluation models were constructed, corresponding to the top seven CPFs-BP across the eight project life-cycle stages. Refer to [Figure 1](#) for the research design and methodological workflow. Developing these models allows for a detailed, stage-specific assessment of each factor’s contribution to BPP, facilitating the identification of critical stages and providing a quantitative basis for targeted improvement strategies.

4. Determining Top Seven CPFs-BP

4.1 Survey I

With three parts contained in the Survey I, Part A consisted of seven questions gathering the respondents’ information, such as the details of BIM-related experience, including the organization type, the number of BIM personnel, participant’s professions and working experience in BIM projects, and the characteristics of BIM projects (i.e., type, figure, and investment nature). Part B was devised to measure the positive influence of 17 CPFs-BP in eight project stages. The five-point Likert scale was used in this survey, with “1” referring to very low and “5” referring to very high. Finally, Part C set out to collect comments supplying additional ways to enhance BPP.

4.2 Data collection

The population of Survey I refers to those who have BIM-related working experience, and the participants were specifically selected via a stratified sampling strategy. Delivered by e-mail, LinkedIn, and hard copy, a total of 200 questionnaires were then sent out to various large-scale organizations in AEC industry, comprising owners, designers, contractors, BIM consultants, academic researchers, and other practitioners. Under such standards, 118 responses were refined, meaning a valid response rate of 59%. Despite the limitation of sample size, the response rate was relatively acceptable compared to other similar studies including 34% in Ozorhon and Karahan^[59], 31.6% in He *et al.*^[43], and 23.48% in Ma *et al.*^[29]. [Figure 2](#) summarizes the relevant information collected in part A of the questionnaire.

In addition, [Table 3](#) summarizes BIM-related information about the respondents. First, BIM was widely applied to all kinds of projects, mainly in residential housing (30%) and commercial facilities (21%). Also, 82.2% of respondents reported that BIM projects had attained government funding. This evidence exactly reflects the present-day megatrend that politics is positively promoting the digital transformation in AEC industry. However, the strategic moves, especially in China, had insufficient influence on BIM adoption. As seen in [Table 3](#), 54% of survey organizations own less than 5 BIM staff, and 66.1% of respondents have participated in no more than five BIM

projects, indicating that BIM practices in China are likely to be stagnated and vulnerable to face the industry transformation by digital technologies.

Table 2. List of CPFs-BP occurrences frequency on literature review.

CPFS-BPs	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Functionality of BIM tools					√		√							√						√	√				√	√		√		
Compatibility of BIM tools		√		√	√	√	√					√		√	√	√		√	√	√							√	√		
Diversity of BIM application areas							√												√	√										
BIM quality						√	√					√		√																
BIM accuracy						√		√					√		√	√				√								√		
BIM usefulness												√	√																	
BIM economy		√		√	√		√	√				√	√		√		√	√		√	√	√	√	√	√		√	√		√
BIM institutional environment	√	√		√			√	√			√	√	√		√		√	√			√	√	√	√	√	√	√	√	√	√
Organizational capability		√		√	√	√	√		√		√	√		√	√		√	√			√		√	√	√	√	√	√	√	√
Stakeholders' roles and responsibilities			√		√			√			√			√		√					√		√				√			
Organizational involvement						√									√			√												
Organizational adaptability to changes				√							√	√		√				√			√	√			√		√	√		
Inter-organization leadership						√					√	√	√	√										√				√		
Contract			√					√		√	√				√			√			√	√			√		√		√	
Inter-organizational trust										√	√			√							√			√					√	
Inter-organization communication		√				√	√				√		√						√	√	√	√	√	√	√	√	√	√	√	√
Information exchange				√		√	√				√	√	√	√	√		√	√	√	√	√	√	√	√			√	√	√	
Ref.	[50]	[51]	[16]	[52]	[14]	[53]	[54]	[55]	[21]	[30]	[56]	[30]	[57]	[13]	[31]	[58]	[59]	[60]	[61]	[62]	[63]	[1]	[23]	[64]	[65]	[66]	[67]	[68]	[69]	[70]

CPFs-BP: critical performance factors of BIM project; BIM: Building Information Modelling.

4.3 Statistical analysis

Four main statistical parameters were measured in the section using a Likert-scale method, as shown in [Table 4](#): average mean, relative importance index (RII), normalized value (NV),

and Cronbach’s alpha (α). Cronbach’s alpha was adopted to assess the reliability of survey data, and its value ranged from 0 to 1. According to Kazado *et al.*^[71], an acceptable α score commonly varies from 0.70 to 0.95. With the same threshold, Gunduz and Abdi^[72] believed it is also supportable if $\alpha \leq 0.99$. Tested by SPSS25.0, the α of 0.944 within the whole survey sample indicated high reliability of questionnaire survey, and the fact that α of each CSF was below 0.944 proved strong inner consistency of all scales.

Table 3. Respondents’ profiles.

Category	Subcategory	Percentage	Category	Subcategory	Percentage
Organization type	Owner	19%	BIM personnel	0-5	54%
	Designers	24%		6-10	17%
	Contractors	23%		11-15	5%
	BIM consultants	3%		20	4%
	Academics	23%		> 20	20%
	Others	8%			
Project type	Residential housing	30%	BIM project quantity	0-5	66.1%
	Commercial facility	21%		6-10	11.0%
	Entertainment facility	8%		11-15	4.2%
	Athletic facility	5%		20	3.4%
	Medical facility	7%		> 20	15.3%
	Transportation facility	12%			
	Industry facility	5%			
	Others	12%			

BIM: Building Information Modelling.

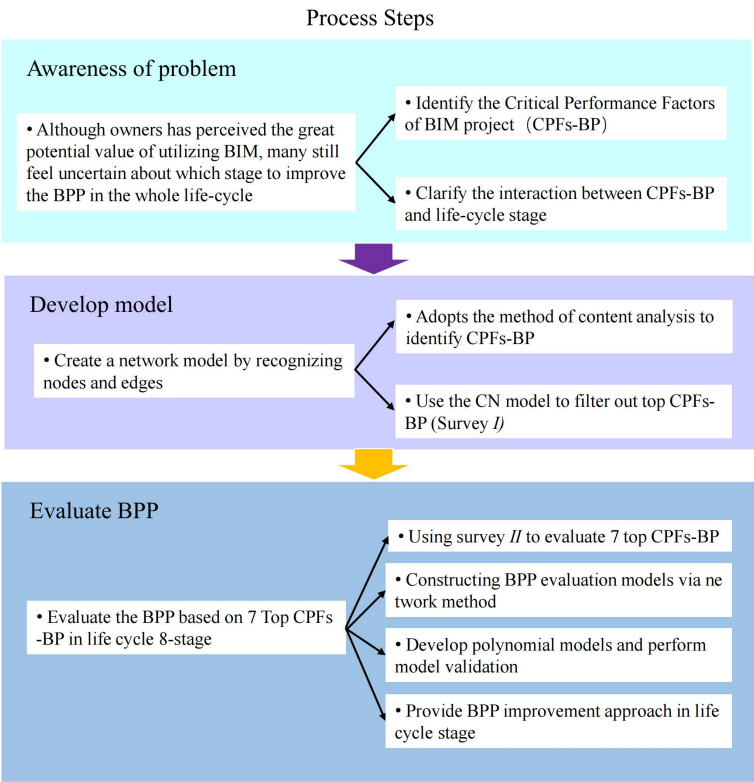


Figure 1. Research design and process steps. CPFs-BP: critical performance factors of BIM project; BPP: BIM project performance; BIM: Building Information Modelling.

Table 4. Rank of CPFs-BP.

	No.	CPFs-BP	Rank	Mean	NV	RII	Cronbach's alpha
Top 7 CPFs-BP	CPFs-BP5	BIM accuracy	1	3.601	1.000	0.721	0.926
	CPFs-BP17	Information exchange	2	3.569	0.856	0.713	0.924
	CPFs-BP6	BIM usefulness	3	3.545	0.750	0.709	0.922
	CPFs-BP4	BIM quality	4	3.521	0.644	0.704	0.921
	CPFs-BP9	Capability of stakeholders' organizations	5	3.510	0.594	0.702	0.932
	CPFs-BP8	BIM Institutional Environment	6	3.498	0.539	0.699	0.921
	CPFs-BP16	Inter-organization communication	7	3.493	0.517	0.699	0.931
	CPFs-BP14	Contract	8	3.478	0.450	0.696	0.929
	CPFs-BP7	BIM economy	9	3.475	0.439	0.695	0.918
	CPFs-BP15	Inter-organizational trust	10	3.456	0.356	0.691	0.941
	CPFs-BP11	Stakeholders' involvement	11	3.448	0.317	0.690	0.915
	CPFs-BP2	Compatibility of BIM tools	12	3.441	0.289	0.688	0.926
	CPFs-BP13	Inter-organization leadership	13	3.434	0.256	0.687	0.927
	CPFs-BP3	Diversity of BIM application areas	14	3.406	0.133	0.681	0.927
	CPFs-BP12	Organizations' adaptability to changes	15	3.386	0.044	0.678	0.94
	CPFs-BP1	Functionality of BIM tools	16	3.380	0.017	0.676	0.894
	CPFs-BP10	Stakeholders' roles and responsibilities	17	3.376	0.000	0.675	0.931

Mean: mean value of statistics; NV: normalized value; RII: relative independence index (an indicator used to measure the independence between feature variables and sample label variables); Cronbach's alpha is a parameter of the reliability of a scale or test; CPFs-BP: critical performance factors of BIM project; BIM: Building Information Modelling.

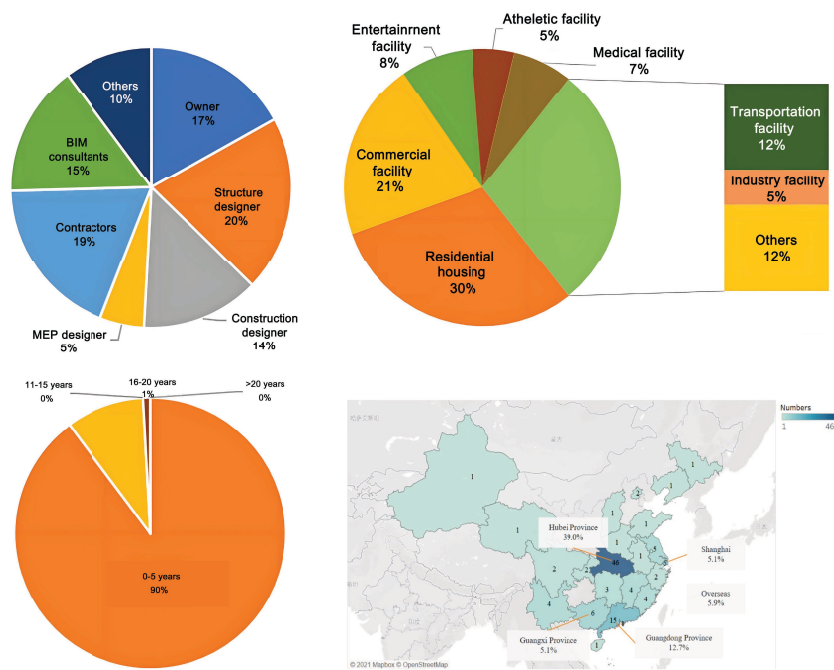


Figure 2. Relevant information collected in part A, Survey I. (a) Professions of participants; (b) Working experience of participants; (c) Categories of BIM projects; (d) Geological distribution of respondents. BIM: Building Information Modelling.

Admittedly, scads of research have already offered several statistical treatments to rank factors’ importance, generally including mean scores^[29,65], NV^[56], and RII^[72], etc. However, it is partial to choose one method of ranking factors in most studies, thus the optimal way is to conduct rank analysis by multiple methods. Therefore, this study might yield two situations, including consistent rank analysis or conflicting rank results. As for the latter situation, it is reasonable that a factor ranked prior to another in any criteria is more critical, which is commensurate with a multi-objective optimization problem. A significant volume of statistical data requires an original processing style in order to improve decision-making power, insight finding, and process optimization skills. Table 4 provides the respective value of mean, NV, and RII. Results of RII analysis were greatly consistent with those of the others, saving more steps to correct the potential conflicting rank results. The reduction from 17 initial CPFs-BP to 7 principal factors was performed using network-parameter-based criteria. For each lifecycle subnetwork, degree centrality, betweenness centrality, and weighted interaction frequency were computed. Factors that consistently ranked in the top quartile across all stages were retained as principal CPFs-BP.

Moreover, previous studies assume that variables with an NV above 0.5 could be viewed as important factors^[56]. At this point, the top seven CPFs-BP were obtained, including CPFS-BP5 (BIM accuracy), CPFS-BP17 (Information exchange), CPFS-BP6 (BIM usefulness), CPFS-BP4 (BIM quality), CPFS-BP9 (Capability of stakeholders’ organizations), CPFS-BP8 (BIM Institutional Environment), and CPFS-BP16 (inter-organization communication).

4.4 Network analysis

Previous analysis had revealed insights about BPP hinging on top seven CPFs-BP, while those statistical methods confront a formidable challenge in exploring the relation between project stages and the CPFs-BP, not least in visualization. Thus, complex network tools such as Gephi were used to shape the complex network of project (CNP) stages and CPFs-BP via network parameters as explained in Table 5.

Table 5. Parameters of complex network.

Parameters	Explanation
Network density	A proportion of potential connections to the actual ones.
Network diameter	The maximum shortest paths between any pair of nodes.
Average path length	The average distance of all node pairs.
Degree	The sum of links for a node.
Betweenness centrality	Measuring the times when a node lies on the shortest path between other node pairs.
Closeness centrality	Scoring each node’s closeness to the others in the network.
Authority and hub	Deciding which node has control over the network.
Page rank	Finding influential nodes whose reach extends beyond direct connections.
Eigenvector centrality	Indicating a strong influence over other nodes in the network.
Weighted degree	Summer the weight of links of one node.
Modularity class	Detect a group of nodes with similar traits and close relationships.

To visualize complex network, project stages over the whole lifecycle are defined as project proposal (P1), feasibility study (P2), concept design (P3), construction documents design (P4), project bidding (P5), construction (P6), completion (P7), and operation and maintenance (P8). First, the global characteristics of CNP can be understood through three related parameters including network diameter (2), average path length (1.467), and network density (0.533). According to Sahoo *et al.*^[73], normal network density is about 0.034 and far lower than that of CNP.

Six measurements are generally used to gauge node function and reveal the individual characteristics, namely degree, closeness centrality, betweenness centrality, authority, hub, and page rank. However, data results failed to differentiate the role of complex network nodes and instead classified the nodes into two explicit groups: project stages and CPFs-BP. Therefore, an additional three parameters were used to make up for this dysfunctional phenomenon, referring to the eigenvector centrality, weighted degree, and modularity class as described in Table 6.

The results of eigenvector centrality and weighted degree are consistent with statistical results. The study also shows that the construction stage (P6) has a more significant impact on BIM projects, followed by the construction document design stage (P4), operation/maintenance (P8), concept design (P3), completion (P7), project bidding (P5), feasibility study (P2), and project proposal (P1).

Regarding network modularization, research also provides some clues about which nodes belong to the same community according to the modularity class given in Table 6.

Table 6. Eigenvector centrality, weighted degree, and modularity of nodes.

Label	Eigenvector centrality	Weighted degree	Modularity class
CPFS-BP5	0.386	28.81	1
CPFS-BP17	0.382	28.55	0
CPFS-BP6	0.379	28.36	2
CPFS-BP4	0.377	28.17	0
CPFS-BP9	0.375	28.08	2
CPFS-BP8	0.374	27.98	0
CPFS-BP16	0.373	27.94	0
P6	0.382	26.77	1
P4	0.379	26.6	2
P8	0.359	25.18	2
P3	0.356	24.97	0
P7	0.355	24.88	0
P5	0.354	24.8	0
P2	0.324	22.7	0
P1	0.314	21.99	0

Eigenvector centrality refer to a network parameter, which mainly measures the influence of a node in the network; Weighted degree refers to the sum of the weights of all edges associated with this node; Modularity class is a metric parameter of the network, used to measure the strength of the network divided into modules (or groups, clusters or communities); CPFS-BP: critical performance factors of BIM project.

Figure 3 shows the network visualization result. Figure 3 offers a clear picture modularized by Gephi, which has three colorized communities: purple nodes (P1, P2, P3, P5, P7, CPFS-BP4, CPFS-BP8, CPFS-BP16, and CPFS-BP17) in Community 1, green nodes (P6 and CPFS-BP5) in Community 2, and orange nodes (P4, P8, CPFS-BP6, and CPFS-BP9) in Community 3. For the other stages, Community 1 brings four relevant aspects together, including project quality, institutional environment, inter-organization communication, and information exchange. Community 2 indicates that practitioners should raise awareness of BIM accuracy, particularly in the construction process. Community 3 highlights the prominent importance of BIM usefulness and the capability of organizations in the construction document design and operation/maintenance stage. This step pinpointed that information exchange and inter-organization communication are of critical significance when conducting the feasibility study and concept design, respectively. Competent stakeholders are highly needed to contribute to the accurate design of construction documents, and a fair and transparent environment of BIM institutions protects project bidding from unnecessary costs. BIM models may be helpful in the building process, and their usefulness and accuracy are crucial for timely completion. In the operation and maintenance stage, there is a tendency to shift focus away from addressing the quality of BIM models, cautioning project partners against overemphasizing certified BIM models in the early stages. The centrality parameter in the network cannot identify the effect of distinct nodes well, which means that there are numerous nodes with varied influences in the same network. Meanwhile, modularization can distinguish the influence of grouping nodes and is consistent with the resulting sorted list. In addition, to regulate the network and achieve the desired state, signals from some nodes must be input. The maximum matching parameter may effectively assess the topological features of numerous point sets in the network.

5. Predicting BPP

5.1 Survey II

Survey II was undertaken to predict BPP using the top seven CPFS-BP. The purpose of Survey II was to find the stages and ways to improve BPP by improving the contributions of participants at various project stages. In the previous part of this paper, the seven CPFS-BP and eight project stages were sorted according to the average and complex network parameters, and the specific weights of the CPFS-BP and project stages could be calculated; moreover, the interaction between CPFS-BP and project stages revealed ways to

improve BPP, so the interaction weights were obtained by multiplication and sorted. In addition, this study summarizes three communities and seven node pairs, respectively, revealing the interaction between CPFs-BP and stages from a network perspective.

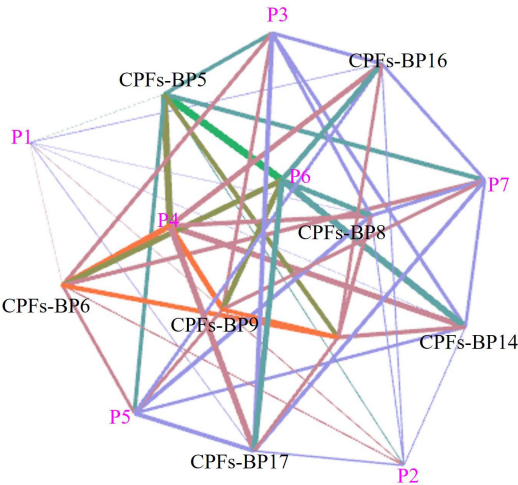


Figure 3. Network visualization by Gephi. CPFs-BP: critical performance factors of BIM project.

5.2 Data collection

The questionnaire consisted of five sections involving (1) respondents’ profiles, incorporating the same questions as Survey I; (2) estimate for the degree of BIM adoption according to different implementation measures in each project stage; (3) evaluation of CPFs-BP in BPP lifecycle; (4) average assessment of BPP concerning quality, schedule, cost, safety, and decision-making; and (5) participants’ feedback on the survey.

Before the survey, an interview attended by five academic professionals was conducted to collect suggestions and comments concerning the design of the initial questionnaire. Subsequently, the revised questionnaires were specifically sent to 20 experts, including three clients, six designers, five contractors, and six BIM consultants. All experts consulted were highly knowledgeable, having either more than 20 years of BIM-related experience or having participated for more than five years on BIM projects. Figure 4 shows the relevant details collected in Survey II, Part A.

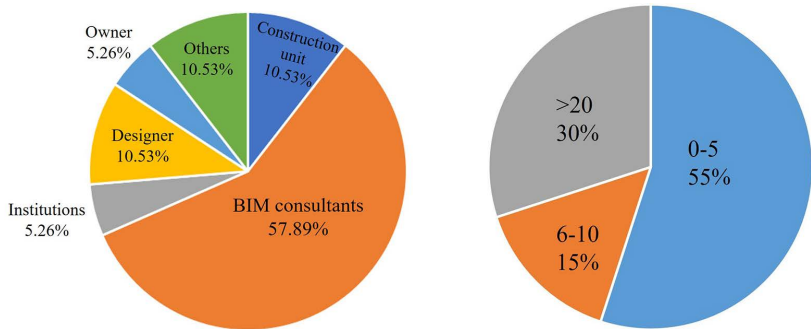


Figure 4. Relevant details collected from Survey II. (a) Professions of participants; (b) Number of BIM projects that participants are involved. BIM: Building Information Modelling.

Here, a five-point Likert scale was adopted to gauge the three variables in eight project stages. As determined by SPSS25.0, the α of collected data was larger than 0.7, with a value of 0.973, showing high reliability of received responses.

5.3 Developing polynomial models

To proceed in the research, the Curve Fitting Toolbox in MATLAB R2021a was adopted to establish fifth-order polynomial models, which achieved the best fitness in predictive data analytics of this study among any other numerical techniques, such as splines, interpolation, and smoothing. Based on the least square method, polynomial curve fitting (polyfit) is an approach in mathematical modelling used to determine a function that is the best fit for a set of data points. A polynomial function with three variables was utilized in each fitting of this study. The three variables have been coded according to eight project stages as shown in Table 7. For instance, DP1 refers to the degree of BIM adoption in the stage of project proposal, C4P1 means the degree to which BIM models meet the project requirements in the stage of project proposal, and BP1 shows BPP in the current stage (P1).

Table 7. Parameter of BPP evaluation.

Project stages	The degree of BIM adoption	CPFs-BP's performance	BPP
P1	DP1	Cn^*P1	BP1
P2	DP2	Cn^*P2	BP2
P3	DP3	Cn^*P3	BP3
P4	DP4	Cn^*P4	BP4
P5	DP5	Cn^*P5	BP5
P6	DP6	Cn^*P6	BP6
P7	DP7	Cn^*P7	BP7
P8	DP8	Cn^*P8	BP8

Cn^* : CPFS-BP4/CPFS-BP5/CPFS-BP6/CPFS-BP8/CPFS-BP9/CPFS-BP16/CPFS-BP17; DP_i refers to the degree of BIM adoption in the stage P_i ; C_iP_j means the degree to which BIM models reach the project requirements in P_i ; BP_j shows the comprehensive performance of BIM projects in P_i ; CPFs-BP: critical performance factors of BIM project; BIM: Building Information Modelling; BPP: BIM project performance.

Therefore, a total of 56 groups of data sets, made up of seven CPFs-BP and eight project stages, were fitted, resulting in 56 3D figures and 56 groups of corresponding coefficients returned by MATLAB R2021a. The figures and coefficients have been given in [Figure S1,S2,S3,S4,S5,S6,S7](#) and [Table S1,S2,S3,S4,S5,S6,S7](#) (focusing on top seven CPFs-BP, in Supplementary materials), respectively.

5.4 Model validation

Generally, three types of parameters are considered to justify the accuracy and efficiency of polynomial fitness. These include the coefficient of determination (R-square), adjusted R-square (adj R-square), and root mean square error (RMSE). RMSE is defined as the standard deviation of the residuals and is applied to verify the experimental results of prediction. The type and goodness of fit are shown in [Table 8](#). In addition to R-square, adjusted R-square, and RMSE, two supplementary checks were performed to ensure model robustness. A 10-fold cross-validation showed that the testing RMSE values were consistent with those in [Table 8](#), indicating that the polynomial models were not overfitted. A simple sensitivity analysis, conducted by varying each CPFs-BP input by $\pm 10\text{--}20\%$, further confirmed the numerical stability of model outputs. Polynomial orders from two to six were compared, and the fifth-order model was selected because it provided the best balance between fit quality and stability.

Table 8. Type and goodness of fit.

Fit name	R-square	Adj R-square	RMSE	Fit name	R-square	Adj R-square	RMSE
CPFs-BP4-P1	0.999496	0.999495	0.023599	CPFs-BP8-P5	0.999478	0.999477	0.04036
CPFs-BP4-P2	0.996906	0.9969	0.05891	CPFs-BP8-P6	0.999549	0.999548	0.02044
CPFs-BP4-P3	0.999845	0.999845	0.01068	CPFs-BP8-P7	0.998383	0.99838	0.032219
CPFs-BP4-P4	0.999319	0.999318	0.012933	CPFs-BP8-P8	0.997736	0.997732	0.051862
CPFs-BP4-P5	0.999471	0.99947	0.03191	CPFs-BP9-P1	0.999767	0.999766	0.014243
CPFs-BP4-P6	0.999757	0.999757	0.012014	CPFs-BP9-P2	0.999942	0.999942	0.137127
CPFs-BP4-P7	0.994808	0.994797	0.082831	CPFs-BP9-P3	0.999548	0.999547	0.023872
CPFs-BP4-P8	0.999029	0.999028	0.051042	CPFs-BP9-P4	0.999866	0.999865	0.013661
CPFs-BP5-P1	0.999405	0.999404	0.028635	CPFs-BP9-P5	0.999146	0.999145	0.023736
CPFs-BP5-P2	0.999125	0.999123	0.454019	CPFs-BP9-P6	0.999988	0.999988	0.080903
CPFs-BP5-P3	0.999177	0.999175	0.038792	CPFs-BP9-P7	0.999813	0.999812	0.046238
CPFs-BP5-P4	0.999902	0.999902	0.013063	CPFs-BP9-P8	0.999923	0.999923	0.049514
CPFs-BP5-P5	0.996426	0.996419	0.052880	CPFs-BP16-P1	0.999651	0.999651	0.026626
CPFs-BP5-P6	0.999694	0.999694	0.025248	CPFs-BP16-P2	0.999918	0.999918	0.193996

CPFs-BP5-P7	0.999716	0.999716	0.051792	CPFs-BP16-P3	0.999931	0.999931	0.069683
CPFs-BP5-P8	0.998971	0.998969	0.048497	CPFs-BP16-P4	0.999745	0.999744	0.019628
CPFs-BP6-P1	0.999152	0.999150	0.025117	CPFs-BP16-P5	0.99934	0.999339	0.028572
CPFs-BP6-P2	0.999936	0.999936	0.108458	CPFs-BP16-P6	0.99826	0.998256	0.034108
CPFs-BP6-P3	0.996899	0.996892	0.052604	CPFs-BP16-P7	0.999361	0.999359	0.027598
CPFs-BP6-P4	0.999678	0.999677	0.016998	CPFs-BP16-P8	0.99987	0.99987	0.062313
CPFs-BP6-P5	0.999844	0.999844	0.026899	CPFs-BP17-P1	0.999887	0.999886	0.055023
CPFs-BP6-P6	0.999738	0.999737	0.011156	CPFs-BP17-P2	0.999899	0.999899	0.221988
CPFs-BP6-P7	0.999818	0.999818	0.024947	CPFs-BP17-P3	0.999874	0.999873	0.014696
CPFs-BP6-P8	0.999407	0.999406	0.045328	CPFs-BP17-P4	0.999897	0.999897	0.071657
CPFs-BP8-P1	0.996432	0.996425	0.053101	CPFs-BP17-P5	0.995771	0.995762	0.042451
CPFs-BP8-P2	0.999915	0.999915	0.226017	CPFs-BP17-P6	0.999775	0.999774	0.018643
CPFs-BP8-P3	0.999446	0.999445	0.019004	CPFs-BP17-P7	0.999544	0.999543	0.04295
CPFs-BP8-P4	0.999368	0.999397	0.016889	CPFs-BP17-P8	0.999562	0.999391	0.062456

CPFs-BP: critical performance factors of BIM project; RMSE: root mean square error.

5.5 Selecting a BPP improvement approach

Based on the interaction weights of stages and performance factors from complex network analysis, the results of BPP improvement approach selection are shown in Table 9.

Table 9. Result of BPP improvement approach selection.

Top CPFs-BP	Stage	Rank result	Top CPFs-BP	Stage	Rank result
CPFs-BP5	P6	0.019737	CPFs-BP16	P3	0.017782
CPFs-BP6	P6	0.019379	CPFs-BP8	P7	0.017773
CPFs-BP6	P4	0.019242	CPFs-BP9	P5	0.017766
CPFs-BP9	P4	0.019039	CPFs-BP16	P7	0.017725
CPFs-BP5	P3	0.018402	CPFs-BP8	P5	0.017719
CPFs-BP5	P7	0.018343	CPFs-BP16	P5	0.017672
CPFs-BP5	P5	0.018288	CPFs-BP5	P2	0.016738
CPFs-BP6	P8	0.018220	CPFs-BP17	P2	0.016565
CPFs-BP17	P3	0.018211	CPFs-BP6	P2	0.016435
CPFs-BP17	P7	0.018153	CPFs-BP4	P2	0.016348
CPFs-BP4	P8	0.018124	CPFs-BP9	P2	0.016261
CPFs-BP17	P5	0.018098	CPFs-BP5	P1	0.016218
CPFs-BP9	P8	0.018028	CPFs-BP8	P2	0.016218
CPFs-BP6	P7	0.018010	CPFs-BP16	P2	0.016175
CPFs-BP4	P3	0.017973	CPFs-BP17	P1	0.016050
CPFs-BP6	P5	0.017956	CPFs-BP6	P1	0.015924
CPFs-BP4	P7	0.017915	CPFs-BP4	P1	0.015840

CPFs-BP9	P3	0.017878	CPFs-BP9	P1	0.015756
CPFs-BP4	P5	0.017861	CPFs-BP8	P1	0.015714
CPFs-BP8	P3	0.017830	CPFs-BP16	P1	0.015672
CPFs-BP9	P7	0.017820			

BPP: BIM project performance; CPFs-BP: critical performance factors of BIM project.

From the results in the first and last rows of Table 9, it can be seen that improving the accuracy of BIM (CPFs-BP5) at the construction stage (P6) was the best way to improve BPP. The stage with the lowest BPP was the project proposal stage (P1), in which it is not advisable to carry out inter-organizational communication (CPFs-BP16). The value of BIM technology in the construction stage was mainly reflected in accuracy, visualization, and high efficiency. BIM accuracy is a factor linked to the deviation between contracts/documents and actual records, and compromises geometric accuracy evaluated in the construction stage^[74]. Faultless BIM models can help decrease the intricacy of projects and result in higher user satisfaction.

In addition, Table 9 shows that the BPP improvement mainly falls in the design stage (P4) and construction stage (P6); while the entire project proposal stage (P1) and feasibility study stage (P2) are not beneficial to BPP. This finding reminds decision-makers to grasp the effective timing in the process of carrying out BIM projects.

6. Discussion

6.1 Specific improvement approach

Derived from Table 9, five additional BPP improvement approaches were chosen by the results of weight ranking, Gephi modularization, and maximum matching, including CPFs-BP9 in P4, CPFs-BP5 in P7, CPFs-BP16 in P3, CPFs-BP8 in P5, and CPFs-BP17 in P2. The first path (CPFs-BP9 in P4) argues for the attention of stakeholders in BIM projects to address their BIM capabilities or competency, particularly during the stage of construction document design, because subtle design errors can have a significant negative impact on project performance. To boost BIM capability, major stakeholders can enrich their understanding of BIM with reference to technology, staff experience, usability, exhaustive use requirements, and deliverable evaluation^[47]. Then, it will be much easier to evaluate the functioning of the degree of BIM adoption and CPFs-BP9, which helps predict and calculate project performance via the polynomial function in Stage 2.

Another path (CPFs-BP5 in P7) reminds practitioners and researchers of focusing on ensuring accurate BIM models when delivering projects. Existing research mainly emphasizes BIM models in the design and construction stages and ignores verification of differences between models and physical conditions in post-construction stages. Similar to an analysis of the optimal path (CPFs-BP5 in P6), improvement of BIM accuracy is part of BPP prediction and assessment.

The third path (CPFs-BP16 in P3) emphasizes the importance of inter-organization communication in the concept design stage. Generally prepared by owners, designers, or BIM consultants, concept drawings comprise much precious information, such as cost and schedule estimates, equipment plot plans, and building layouts^[75]. Therefore, patiently shaping consensus on BIM models is necessary for designers and others to adapt to ever-changing conditions/data due to complex interaction^[76], and to prevent design deficiency^[77]. Two critical elements found to promote inter-organization communication include mature and transparent BIM implementation and integrated teams^[53]. Overall, it should be noted that further research into this path is required to predict BPP more accurately, particularly as it refers to effective improvements and quantitative evaluation of communication.

Additional reasonable paths (CPFs-BP8 in P5) show the close connection between the BIM institutional environment and the project bidding process. BIM technology is applied to gain effective cost management from the owners' perspective at the project bidding stage, where contractors may encounter intense competition to deliver BIM models that are as accurate as possible^[78]. Successful BIM models must be in line with the content of the institutional environment, which consists of industry standards and technical needs, policy and regulations, and organizational rules^[32].

BIM models have been regarded as useful platforms for information sharing that provide services for project stakeholders, especially in the design and construction stages. Thus, the underappreciated path (CPFs-BP 17 in P2), despite a low ranking of interactive weight, discovers the neglected fact that effective information exchange is valuable to feasibility studies. As suggested by Che Ibrahim *et al.*^[79], information sharing can be enhanced by facilitating communication, accountability, and trust between project parties. Also addressed for effective information flow were other actions, such as early participation on the part of project stakeholders and information clarification^[50]. Overall, project participants can take measures in feasibility studies to enhance information exchange but may still feel uncertain about the increased degree of project performance. The identified improvement paths can be operationalized through several practical measures for project participants. For CPFs-BP9, organizations may enhance BIM capability by establishing structured BIM training, clarifying document-review procedures, and standardizing modelling workflows. For CPFs-BP5, BIM accuracy can be improved through routine clash audits, field-model consistency checks, and

discipline-to-discipline model reconciliation. For CPFs-BP16 and CPFs-BP17, effective communication and information exchange can be supported by early coordination meetings, shared CDE platforms, and explicit information-release protocols. For CPFs-BP8, aligning bidding documents with institutional BIM standards can guide contractors toward compliant model delivery. These actions translate the identified paths into feasible project practices.

6.2 BPP improvement in the top seven CPFs-BP

A growing interest in BIM adoption has promoted remarkable research into diverse areas. This study develops quantified improve approach of BPP, considering the degree of BIM adoption and the seven top CPFs-BP over the project lifecycle. The most effective way for major stakeholders is to pay more attention to improve BIM model accuracy at the construction stage. Interestingly, three special optimization paths were detected through multiple views of interactive weight, modularization results and maximum matching results by Gephi. Specifically, project stakeholders need to raise concerns about the capabilities of stakeholder's organizations in designing construction documents, BIM accuracy in the completion stage, inter-organization communication in concept design, the BIM institutional environment in project bidding, and information exchange in feasibility studies.

BIM accuracy refers to how precisely the BIM reflects the physical real-world conditions of a project, i.e., how closely the BIM's geometry/data represents as-built conditions in the field. Quantity takeoff accuracy, discrepancies between each discipline's models, average number of generic objects per assembly, and constructability (i.e., the ability to construct from the model) are able to jointly depict BIM accuracy^[13]. Many studies have pointed out that cooperation is closely related to project performance, and frequent information exchange is the basic element of cooperation^[4]. BIM usefulness refers to how useful the model information and geometry are over the project lifecycle. Some variables to measure this might be how often the model is accessed for different purposes, ease of construction documentation creation, and reliability of model data for end users during operation and maintenance (i.e., how reliable data extracted from the model is)^[13]. BIM quality refers to how well a BIM fulfills desired requirements. Liu *et al.*^[4] offered some detailed metrics, including the ratio of number of warnings to number of objects, criticality of warnings (some warnings are more critical than others; e.g., a warning related to a column is more critical than that of a door), consistency of 3D model and 2D references (i.e., number of errors in reference to 2D deliverables), and analytical reporting quality (structural analysis quality, day lighting simulation report quality, energy simulation report quality, etc.). Organizational competitive capability includes competency of individual stakeholders, capability and maturity of architecture, engineering, construction, and operation (AECO) organizations, and maturity of using BIM technology and workflows^[6]. These core objectives are to facilitate AECO stakeholders in the successful delivery of BIM projects. Lack of BIM knowledge among team members leads to the disadvantage of BIM adoption^[33]. BIM Institutional Environment refers to the regulatory system formed by BIM-related standards and technical requirements, organizational rules and requirements, and policy and legal issues to ensure BIM implementation within the project context^[32]. An institutional environment within a BIM-based project is required to facilitate BIM governance and ensure collaborative working among project teams^[32]. In addition, Lee *et al.*^[5] argued that inter-organizational trust may influence the effect of joint-contract functions on project performance. Inter-organizational trust is a firm's expectation that another firm will not behave opportunistically. Inter-organizational trust thus allows two firms to exchange information and share responsibilities for decision making^[80]. Trust relationships are conducive to inspiring the diffusion of valuable knowledge and innovations, which lessens opportunism and contributes to project performance^[81].

The dominance of specific CPFs-BP at particular stages can be explained by the functional needs of each life-cycle phase. Stakeholder capability (CPFs-BP9) becomes critical during construction document design because modeling quality relies heavily on organizational competence. BIM accuracy (CPFs-BP5) is most influential in the completion stage, where as-built verification determines project outcomes. Communication (CPFs-BP16) and information exchange (CPFs-BP17) are essential during conceptual design and feasibility studies, as early coordination shapes subsequent decisions. The BIM institutional environment (CPFs-BP8) has a greater impact during bidding because standards and regulations directly guide model requirements.

These findings align with previous studies emphasizing BIM accuracy, organizational competency, and inter-organizational communication as critical factors for project performance^[74,82-84]. While the survey data mostly represent Chinese AEC projects, the fundamental principles are likely to apply across locations and project types, as long as the local institutional environment, stakeholder capabilities, and project scale are properly recognized.

More importantly, the most distinctive finding of this study is that BIM-enabled project performance improvement does not rely solely on the most highly weighted CPFs-BP, but rather on a set of stage-specific and sometimes underappreciated improvement paths identified through complex network analysis. Unlike prior studies that primarily rank critical factors based on overall importance or frequency, this study integrates interactive weight analysis, modularization, and maximum matching to reveal how specific CPFs-BP exert dominant influence at particular life-cycle stages.

7. Conclusion and Recommendations

Growing interest in BIM applications has spurred ground-breaking research in various fields, including CPFs-BP identification and BPP improvement. This study determined seven principal CPFs-BP by both statistical analysis and complex network analysis,

quantified and illustrated the connections between CPFs-BP and life-cycle stages, and developed models of BPP prediction and approaches of BPP improvement. In summary, this study developed a unique methodology to predict and improve BPP based on complex networks and polynomial models, i.e., identifying at which stage BPP may be improved.

Remarkably, the manuscript finds interesting conclusions using different interactive weight views. In particular, stakeholders in BIM projects should pay attention to 5 matching results: Capability of stakeholders' organizations (CPFs-BP9) in the project proposal stage (P1), BIM accuracy (CPFs-BP5) in the completion stage (P7), inter-organizational communication (CPFs-BP16) in the conceptual design stage (P3), the BIM institutional environment (CPFs-BP8) in the project bidding stage (P5), and Information exchange (CPFs-BP17) in the conceptual design stage (P3).

The findings of this study have important policy implications for both governmental and organizational decision-making in the AEC industry. Policymakers can improve BIM adoption and project performance by highlighting crucial CPFs-BP and their impact at various stages of the project. Nonetheless, the study has limitations, such as a sample drawn mostly from China and an emphasis on large-scale projects, which may limit the generalizability of the findings. To improve practical applicability, future research could extend this framework to other geographies and project types, incorporate other CPFs-BP, and evaluate the prediction and improvement models using longitudinal case studies.

Supplementary materials

The supplementary material for this article is available at: [Supplementary materials](#).

Declarations

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Authors contribution

Yang L: Writing-review & editing, visualization, methodology, formal analysis, conceptualization.

Hu X: Writing-original draft, visualization, methodology, data curation.

Zhao X: Writing-review & editing, validation, supervision.

Conflicts of interest

Xianbo Zhao is an Editorial Board Member of *Journal of Building Design and Environment*. The other authors declare no conflicts of interest.

Ethical approval

This study involved voluntary participation of professionals through anonymous questionnaires. According to institutional guidelines, formal ethical approval was not required.

Consent to participate

Informed consent was obtained from all participants.

Consent for publication

Not applicable.

Availability of data and materials

All data and models generated and used to support the findings of this study are available from the corresponding author upon reasonable request.

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