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Research Article

Decision-Making Evaluation and Optimization Strategies for Construction EPC Project Developers Utilizing BIM Technology

Yujie Wu,[1] **Xiaoming He**,[2] **Tianyi Cui**,[3] **and Mengze Wu**[4]

[1]*School of Civil Engineering, Chongqing University, Chongqing, China*
[2]*Civil Engineering and Transportation Engineering, Yellow River Conservancy Technical Institute, Kaifeng 475004, China*
[3]*School of Engineering, Cardiff University, Cardiff, CF24 3AA, UK*
[4]*School of AI and Advanced Computing, Xi'an Jiaotong-Liverpool University, Suzhou 215123, China*

Correspondence should be addressed to Tianyi Cui; cuit2@cardiff.ac.uk

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In the context of the advancing construction engineering field in China, there has been a significant increase in the adoption of building information modeling (BIM) technology within engineering–procurement–construction (EPC) projects. This emerging technology is expected to significantly influence the decision-making practices of professionals in the construction and engineering domain. Consequently, there is an urgent need for comprehensive research focused on construction management specifically pertaining to the effectiveness of construction developer management. This study examines seven representative EPC projects where BIM technology was implemented and it considers various factors that have the potential to influence project decision-making while taking into account time and cost considerations. A comprehensive multidimensional evaluation method that combines the analytic hierarchy process (AHP) and the fuzzy comprehensive evaluation method is introduced in this study. The results of this study emphasize that the efficiency enhancement strategies derived from the judgment indicator method demonstrate favorable practical outcomes. This research highlights the importance of a comprehensive evaluation method combining the AHP and the fuzzy comprehensive evaluation method to enhance decision-making efficiency for construction developer management staff.

1. Introduction

The engineering–procurement–construction (EPC) projects method is widely practised in the engineering and construction industry. This model reduces the management work of the development company based on its advantages in terms of a simple contractual relationship, a fixed lump sum price, and the management of a single responsibility system. Notably, EPC projects have been increasingly complex in the whole process because it is a turnkey job at the time of contracting. This feature requires a high integration of all processes [1]. The introduction of digital applications in the design, procurement, and construction phases could be an effective approach to meeting the requirements above. Nevertheless, there is a dearth of empirical research regarding the impact of digital applications on EPC project management.

The design phase of the EPC model includes scheme design, organization design, drawing design, and management design, and the design phase has a cost impact of approximately 35%–75% of the overall project [2]. Therefore, the use of building information modeling (BIM) technology makes it possible to compare various options during the design phase, optimizing the design, and drawing reviews of various disciplines to optimize resource allocation and save on costs at the source. The importance of BIM application in construction fields has been revealed in recent decades, and this kind of computer-aided management support is changing the traditional construction industry. The latest research shows that the integration of BIM technology and the EPC pattern positively influences project candidates in organization type [3]. Additionally, the results of recent analyses indicate that decision-making in the engineering phase is the most important factor influencing management efficiency and productivity [4].

While the integration of BIM applications in EPC projects has garnered substantial attention within the engineering domain [5, 6], a conspicuous void exists in the literature concerning the practical implications of these technologies on the decision-making behavior of industry practitioners. Although a handful of studies have ventured into exploring how BIM facilitates decision-making throughout a project's lifecycle [7], they often overlook a pivotal player—the construction developer's management staff. This oversight is particularly striking given this group's immediate influence on on-site management practices, which are themselves undergoing a radical transformation in response to the advent of digital construction sites [8].

The unique role of developer management staff in navigating this digital shift is further complicated by the adoption of the EPC model, which redistributes traditional management responsibilities and necessitates adaptive decision-making strategies [9]. Despite the transformative potential of BIM in enhancing project efficiency, cost-effectiveness, and overall quality under the EPC framework, empirical investigations into how developer managers leverage BIM to inform their decisions remain scarce. This paucity of research not only undermines our understanding of real-world BIM implementation challenges but also hampers the ability of the construction sector to fully capitalize on the automation and digitization wave sweeping across industries globally [10]. Therefore, there is an urgent need to bridge this research gap by examining the decision-making processes of construction developer management staff in the context of EPC projects powered by BIM technology. Such an endeavor promises to illuminate pathways for optimizing on-site operations, enhancing project outcomes, and ultimately, propelling the construction industry forward in alignment with the era of Industry 4.0 [11]. BIM represents a paradigm shift in the way construction projects are conceptualized, designed, and executed. BIM not only involves tools and software (referred to as BIM technology) but also encompasses the fundamental understanding and expertise (referred to as BIM knowledge) that underpin its successful implementation. The utilization of BIM technology in EPC projects is not a novel concept, and it appears that construction management staff should harness this technology to enhance the effectiveness of decision-making processes, thereby facilitating the timely completion of projects.

This research aims to investigate whether BIM technology is now effective in improving management efficiency among construction developer management staff. Additionally, it also seeks to provide a more feasible and efficient evaluation method based on decision-making analysis for developer management staff working on EPC projects with the utilization of BIM. This study aims to evaluate the effectiveness of BIM technology in enhancing management efficiency among construction developer management staff within EPC projects. It investigates whether BIM improves decision-making processes and seeks to develop a feasible and efficient evaluation method for these processes. The research focuses on the subjective initiative of construction developers, analyzing how BIM technology can optimize decision-making and proposing strategies for improvement

1.1. Literature Review

1.1.1. Application of BIM Technology in EPC Projects. BIM is defined as a technology that can simulate construction [12], and this technology can analyze the entire life circle of construction based on a multitude of digital parameters [13]. The application of BIM is growing in popularity due to its features, and it is generally categorized into three main types. The first and the most fundamental category involves 3D spatial modeling, the second is known as 4D, which incorporates time parameters. A concept receiving significant attention today is 5D BIM [14], which consists of cost calculation throughout the entire life cycle. Currently, there is a wide variety of BIM tools available on the market, which have been widely accepted and continuously developed globally, becoming the standard in the construction industry. While technology continues to innovate, there are challenges in terms of localization adaptation. In practice, the most commonly used tools include Revit (for model creation), Navisworks (for model integration and clash detection), 3D Max (for rendering images), and Lumion (for rendering images and creating walkthrough videos). This article mainly focuses on Revit as the primary BIM tool.

The EPC method originated in the United States (U.S.) in the 1970s [15] and has since gained widespread adoption in the construction industry worldwide [16]. Although the EPC mode offers advantages of reducing uncertain costs, improving management efficiency, driving contractors' motivation, etc., when comparing the traditional design-bid-build (DBB) method [17], the intricate processes encompassing design, procurement, and construction phases need a large number of digital computational abilities and information analysis capabilities [18] from both developers and contractors. The introduction of BIM technology with the advantages of parameterization, visualization, and coordination can effectively improve management efficiency and construction quality. Unlike standard BIM applications that primarily focus on individual phases of a construction project, BIM-based EPC embodies a holistic approach where BIM serves as the backbone for seamless coordination across design, procurement, and construction stages. This systemic application not only addresses the historical issue of fragmented information flow in EPC projects but also enhances collaboration and informed decision-making among all stakeholders.

Under the conventional EPC model, developers often maintain a supervisory role, delegating the bulk of the project execution to contractors. However, the integration of BIM in EPC projects empowers developers to engage more actively in project oversight without necessarily participating in granular tasks. By leveraging real-time project data and analytics provided by BIM, developers can monitor progress, assess risks, and make strategic interventions, thereby ensuring adherence to project objectives and enhancing overall project control [19]. The unique position of BIM in EPC projects is further highlighted by its ability to facilitate communication and coordination among designers, suppliers, and constructors, fostering an environment where decisions are data-driven and synchronized [20]. This stands in contrast to traditional BIM uses that may be more isolated to specific project phases or departments. However, it is not yet clear whether BIM technology is making a difference in frontline management and whether it is actually helping staff with their project management work.

BIM technology has been extensively applied in EPC projects to address the limitations of the traditional EPC model, which often suffers from low information flow during engineering design, procurement, and construction phases. While BIM facilitates resource deployment and contractor management, the role of developer management staff remains largely supervisory, especially under the EPC model where contractors handle the bulk of project execution. This research explores the novel application of BIM technology in enhancing the decision-making efficiency of developer management staff within EPC projects.

Existing literature [21, 22] suggests that BIM-based EPC represents a new frontier in construction management, redefining roles, and decision-making patterns among stakeholders. However, the unique decision-making processes of developer managers in these projects have not been thoroughly examined. This study aims to fill this gap by investigating how BIM technology can improve management efficiency, providing a more feasible and efficient evaluation method based on decision-making analysis. It offers a comprehensive discussion on this topic and proposes optimization strategies for integrating BIM within EPC frameworks, ultimately contributing to more efficient, cost-effective, and sustainable construction projects.

1.1.2. Development of the Research on Decision-Making. In the 1960s, criticisms of behavioral decision theory emerged, which greatly promoted the development of decision-making theory. The emergence of behavioral decision theory apparently brings the boom of decision-making research. However, the decision maker's own values and preferences are the subject of the decision-making. Making a decision involves considering numerous options and the goals and aspirations associated with that decision. A concise overview of the development and definition of decision-making and the reason for the continued research on decision-making lies in its profound influence on judgment and choice. Furthermore, it is established that a wrong decision can have a negative effect on the quality of the result, while a right decision can significantly increase people's explanatory power [23], as evidenced by Lope's investigation.

In the twenty-first century studies, most researchers have focused on the decisions of managers or senior company leaders. Brousseau et al. [24] divided the decision-making style into two different aspects according to their observation: one mull over extensive information before making decisions, while the other involves creating a single or multiple focal points to assist in decision-making. The preceding study reveals managers' decision-making processes in different settings. Sofo et al. [25] also studied the influence of decision-making on sociology in diverse objects and summarized decisions matter at every managerial level. Their research suggests that the effects of decisions would often be reflected in the time dimension from senior management to the operational level. These articles tend to concentrate on the senior manager of the company in the study of decision-making. The bulk of research on construction developers' decision-making predominantly centers on investigating the interactions between government entities and developers [26, 27] In the examination of decision-making within the construction domain, prior literature has primarily emphasized the influence of new technologies [28] while allocating relatively less attention to scrutinizing the decision-making processes of management staff themselves. However, the developer management staff was often able to directly influence the outcome of the engineering project. It is crucial to identify and develop a decision-support methodology and optimization design strategy tailored specifically for the needs of developer management personnel. A three-stage decision support method was developed to help design and operationalize in a maritime emergency [29]. This decision optimization approach combines intelligent algorithms and TOPSIS decision support methods. Further, an optimal design option [30] based on a genetic algorithm generating a multiobjective optimization is used to develop appropriate building retrofit strategies, enabling the subjective opinions of the users to be linked to the final design solutions

In the realm of engineering and construction projects, a comprehensive understanding of the evaluation and optimization processes with BIM technology becomes imperative. Evaluation, as a systematic process, typically encompasses assessing project performance against predefined criteria, such as cost-effectiveness, time efficiency, and sustainability [31]. It often involves both quantitative methods, like cost–benefit analysis and earned value management, and qualitative assessments, including stakeholder satisfaction and environmental impact evaluations.

The optimization strategies in construction projects have expanded beyond traditional design, scheduling, and resource allocation due to the revolutionary impact of BIM technology [32]. Unlike previous optimization methods, BIM's innovative approach unifies all project elements into a cohesive digital model, promoting real-time collaboration, automatic clash detection, and data-driven decision-making [33]. This not only streamlines project planning, design, construction, and management but also facilitates detailed visualizations and performance simulations for enhanced evaluation [34]. Moreover, BIM optimizes outcomes by preemptively identifying issues, improving buildability, and streamlining project coordination. Yet, despite the acknowledged advantages of BIM, its specific effects on decision-making at the microlevel in EPC projects, especially concerning site management, are understudied. Existing research [35] predominantly focuses on high-level strategic decisions, neglecting the day-to-day choices made by project management staff that are pivotal to harnessing BIM's full potential.

To address this gap, recent studies [36] delve into how BIM technologies reshape decision-making processes among developer management staff in EPC projects. These investigations reveal the mechanisms through which BIM boosts

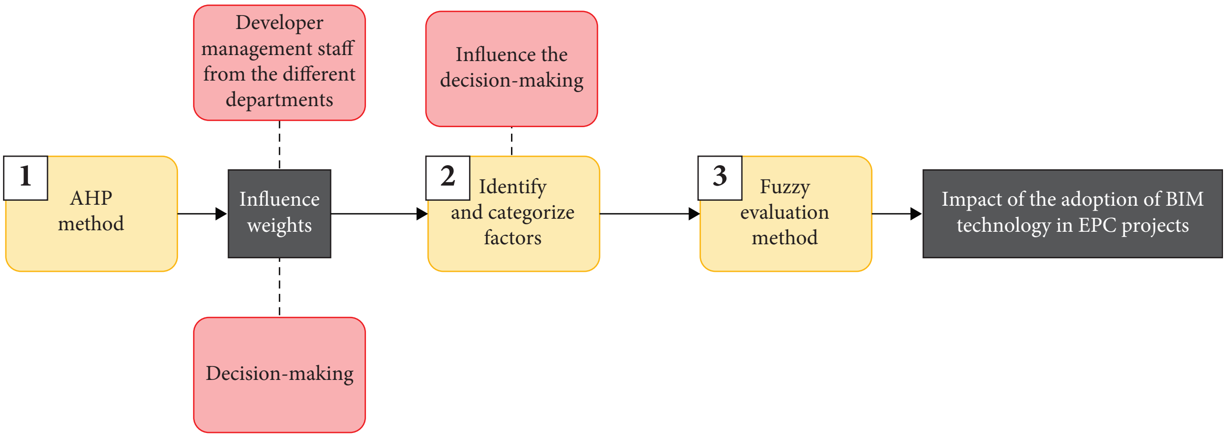

Figure 1: Research path.

project outcomes, offering insights into practical strategies for more effective technology integration. This research contributes to a more nuanced understanding of the operational implications of advanced technologies in construction management, paving the way for optimized project execution and enhanced industry practices but is still slightly broad. In summary, the manuscript highlights the novel ways BIM transforms optimization and decision-making in construction projects, particularly in EPC contexts. It underscores the importance of studying the decision-making dynamics influenced by BIM at a more specific object—project management staff, advocating for a deeper exploration of this area to fully realize the technology's potential.

2. Methodology

More research on senior managers and multiobjective analysis in the field of decision-making are conducted by the literature related to this field. Regarding the choice of method, there is a prevalence of using either subjective or objective assignment methods applied singularly and less in combination. Habibi et al. [37] identified the performance priorities of best practise (BP) for EPC projects by distributing questionnaires to relevant practitioners and testing them with different statistical analyses of the data. In the field of EPC projects in the energy industry, TOPSIS and fuzzy comprehensive evaluation methods are also commonly used as evaluation methods for multicriteria group decision-making. A comparison between the AHP and TOPSIS methodologies [38] will be effective for selection issues in the area of employee representative selection. Whereas fuzzy AHP is better adapted to time complexity. In summary, this study commences by selecting a set of representative EPC projects based on BIM technology for an in-depth examination of decision-making among developer management staff. In order to integrate the advantages of the above methods and ensure the independent objectivity of each phase, the study is organized into the following three main phases: with the initial phase utilizing the analytic hierarchy process (AHP) method to derive the influence weights of developer management staff from the different departments when making decisions about the project. Then, identify and categorize various factors that could potentially influence the decision-making on projects. Lastly, employ the fuzzy evaluation method to analyze and integrate these factors in order to investigate the extent to which the adoption of BIM technology in EPC projects is impacted by the project construction developer. The specific research path is shown in Figure 1.

2.1. Identification of Research Projects. The initial phase of this study is to select a valid and accurate sample set of subjects. In the selection process of the construction project, the following three aspects were taken into consideration. First, the construction project could not be a pilot project for the *Four New* (new technology, new techniques, new materials, new equipment), otherwise, the technical immaturity would influence the decision of the managers and deviate from the general context of this research. Second, the construction project should not be a mega project, otherwise, the scale of the project will affect the management decision analysis. Finally, the overall quality of the management staff should be at the industry's average level, and the previous exposure to the project is mainly traditional engineering projects. Sample selection sources should be plentiful based on the above aspects. To overcome these issues, our study meticulously chose a sample of seven BIM-based EPC projects from China, ensuring that they covered a diverse range of project types, such as residential and highway construction. This choice is bolstered by recent third-party reports indicating a robust BIM market in China, with a value surpassing 12 billion yuan [39].

Our sample selection strategy was guided by the intent to reflect the varying degrees of BIM policy implementation across different provinces. Provinces like Chongqing and those along the developed coastal regions have been more proactive in adopting BIM technologies for EPC projects, whereas less developed inland areas, exemplified by Henan, have demonstrated a more cautious approach toward local policy implementation. To capture this spectrum of BIM adoption, we included projects from Chongqing, Sichuan, and Henan, spanning both Eastern and Southwestern China. This geographical spread enriches the sample's diversity, allowing us to embrace the nuances of BIM deployment in

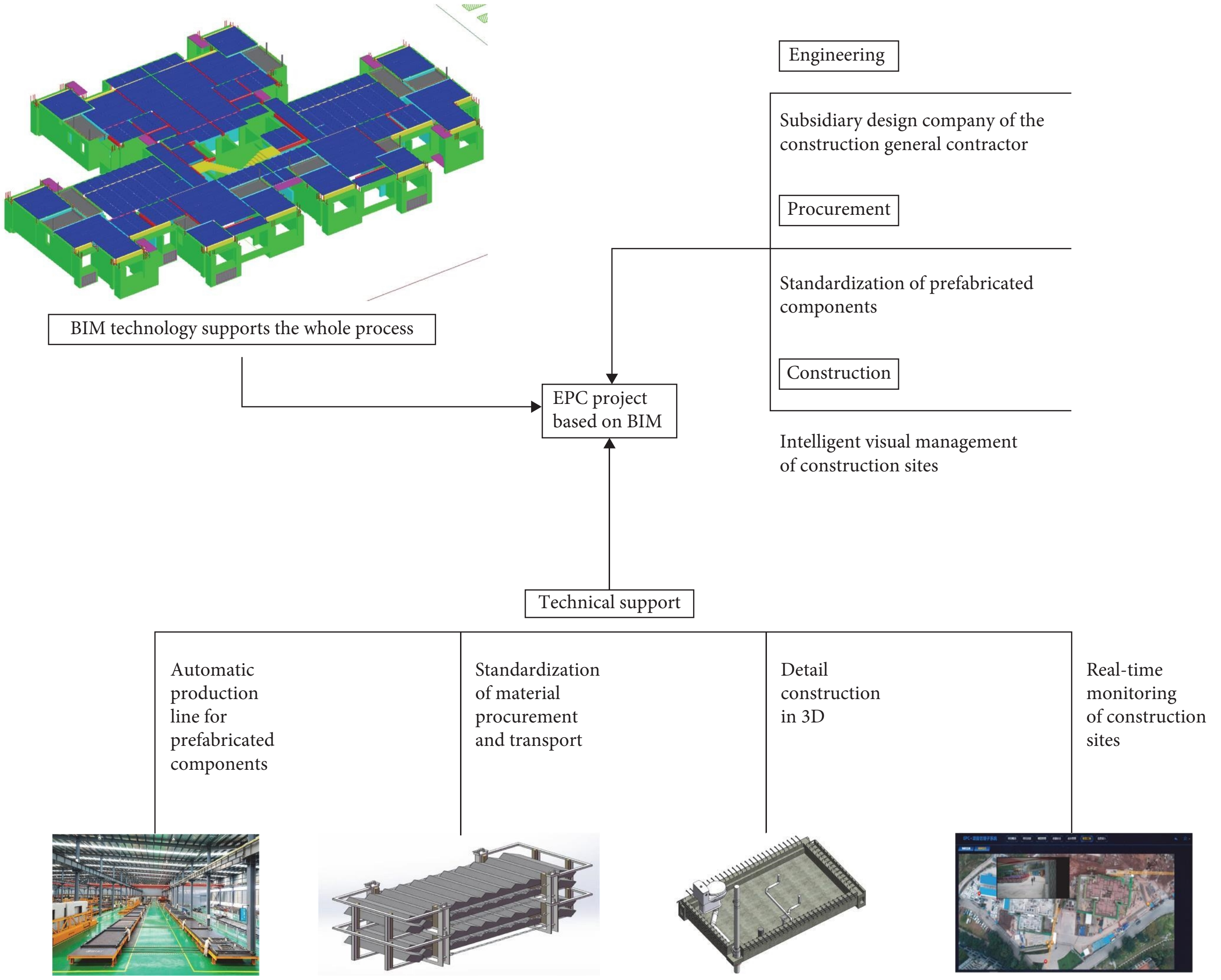

Figure 2: System architecture of a typical EPC project based on BIM.

contrasting regional settings. Moreover, the projects were chosen based on the expertise level of the management teams, which mirrored the average industry standard, mostly comprising individuals with backgrounds in traditional engineering projects. This criterion helped to ensure that the findings would be applicable to the majority of EPC projects in China, rather than being skewed by projects involving highly specialized or exceptionally experienced personnel. By incorporating projects from multiple sectors, such as residential buildings and highways, we aimed to mirror the heterogeneity of the Chinese construction sector. This sectoral breadth ensures that our findings are not confined to any particular type of construction, but rather reflect the broader industry landscape. Direct engagement through field interviews was employed, despite the low response rates [40] typical in the construction sector, to collect high-quality, firsthand data. The projects, which ranged in scale with floor areas not exceeding 100,000 m^2, were selected from reputable developers, designers, and constructors, making them emblematic of typical EPC projects undergoing technological transition in China.

In summary, although our sample size is limited to seven projects, the meticulous selection process, based on project characteristics, regional representation, and rigorous data collection methods, supports the representativeness of our sample for BIM-enabled EPC projects in China. These projects serve as a microcosm of the industry's technological evolution and operational realities, providing a robust foundation for insights that are applicable to a wide array of similar projects across the country. Based on the aforementioned criteria, the overall system architecture of the generic project is summarized and illustrated in Figure 2.

2.2. Weighting of Research Participants. An organizational chart of the subject of the study was constructed as Figure 3 based on the general composition of the management staff (including one top manager) of the developer in general. To better determine the importance of decisions made by the developer's management staff in each department to the impact of the project, the first phase of the survey was to rank the weighting of the results for each professional. The following steps can be used for weighting assessment when

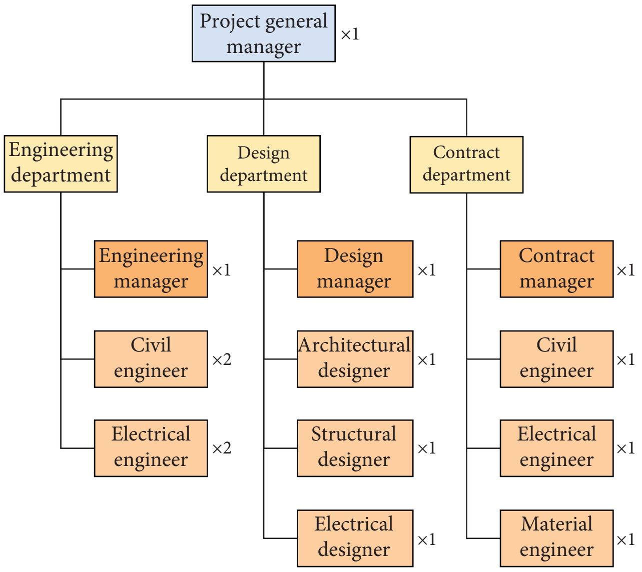

Figure 3: Organizational chart.

studying decision-making analysis for developer staff: define the purpose of the weighting assessment to ensure the validity of the decision analysis; determine the criteria for weighting assessment based on the purpose of the decision analysis to ensure that the weighting assessment is universally applicable.

There are generally three broad categories of methods for obtaining weights: subjective, objective, and combined weighting depending on the source. In the three types of weighting, objective weighting methods are sometimes limited by the inability to obtain true weight, while combined weighting methods may not effectively reflect differences in indicator importance [41], so this leads to the conclusion that subjective weighting is often a more suitable method for weighting the impact of people's decisions in this study. However, precise quantitative information is not normally given in subjective assignment methods. Therefore, in order to be more impartial, the weighting of the definition in this study was ascertained after interaction with the project general manager and feedback from other staff on site such as construction staff and supervisors, totaling 147 individuals (with a minimum of 20 interviewees per project). The process employed a mixed-methods approach, integrating both qualitative insights through interviews and quantitative analysis via observed data. It aimed to identify and weigh factors influencing decision-making in construction projects, focusing particularly on the subjective weighting method. Participants were engaged in discussions to understand their perceptions of which factors were most influential in decision-making processes. The interviews followed a semistructured format, allowing for both guided questions and open-ended exploration of responses. The first concrete step is to define two indicators (time: time on site; cost: amount of contract involved) as being the most relevant to the decision-making of the projects. Then, the interactions with the project general manager and site staff to ascertain the weighting of decision-making factors. Observational recordings of time allocation by different departments (engineering, design, contracts) across various projects lead to the creation of Figure 4. This cost a period (1 week) of ongoing observation to gather sufficient data on departmental activities. In this study, due to the variability in the number of construction developer managers across different projects, the average time spent on site was chosen as the representative time metric. Meanwhile, it is noteworthy that two of the projects' developers lacked an on-site record of the design and contracts departments. Figure 5 is generated by compilation of contract amounts under different directories, indicating a post hoc analysis of financial records. This step required access to historical financial data and data analysis.

Considering the limited number of impact factors and the desire for an easy-to-use and transparent weight analysis process, the AHP proposed by Saaty proves to be a fitting choice for weight analysis. Notably, AHP is also one of the most extensively utilized methods for multiattribute decision-making methods [42] and is also extensively employed in the field of construction management [43].

The step first determined a specific purpose after using the AHP method for standard measurement: decision-making on projects (DP). As shown in Table 1, DP consists of six subcriteria: engineering department time (ET), engineering department cost (EC), design department time (DT), design department cost (DC), contract department time (CT), and contract department cost (CC). Each criterion is processed with nine measurement standards to evaluate the components of (DP), from 1 = "both are equally important compared to each other," 3 = "the former is somewhat more important than the latter compared to each other," 5 = "the former is definitely more important than the latter compared to each other," 7 = "the former is much more important than the latter compared to each other," and 9 = "the former is extremely more important than the latter compared to each other" and 2, 4, 6, 8 are intermediate values [44]. The results are calculated from the seven projects of total 96 construction developer management staff as its arithmetic mean (two decimal places are retained) and then displayed as a judgment matrix in Table 1.

After constructing the judgment matrix, all the elements are evaluated two by two, and hierarchical sorting is carried out to arrange the order of importance, the specific calculations can be carried out based on the judgment matrix A, and the calculations ensure that it can meet the conditions of the eigenroots and eigenvectors of $AW = \lambda_{\max} W$. Here, the largest eigenroot of A is $\lambda_{\max}$, the eigenvector corresponding to the regularization of $\lambda_{\max}$ is W, and wi is the component of W, which refers to the weights and corresponds to its corresponding element in a single order. The weights (weight coefficients) of each factor a_{ij} on the target layer are calculated using the judgment matrix. The specific calculation formula [45] is as follows:

$$\overline{W}_i = \sqrt[n]{\prod_{j=1}^{n} a_{ij}}, \mathrm{i}, \mathrm{j} = 1, 2, \cdots, \mathrm{n}, \tag{1}$$

$$W_i = \frac{\overline{W}_i}{\sum_{j=1}^{n} \overline{W}_j}, \tag{2}$$

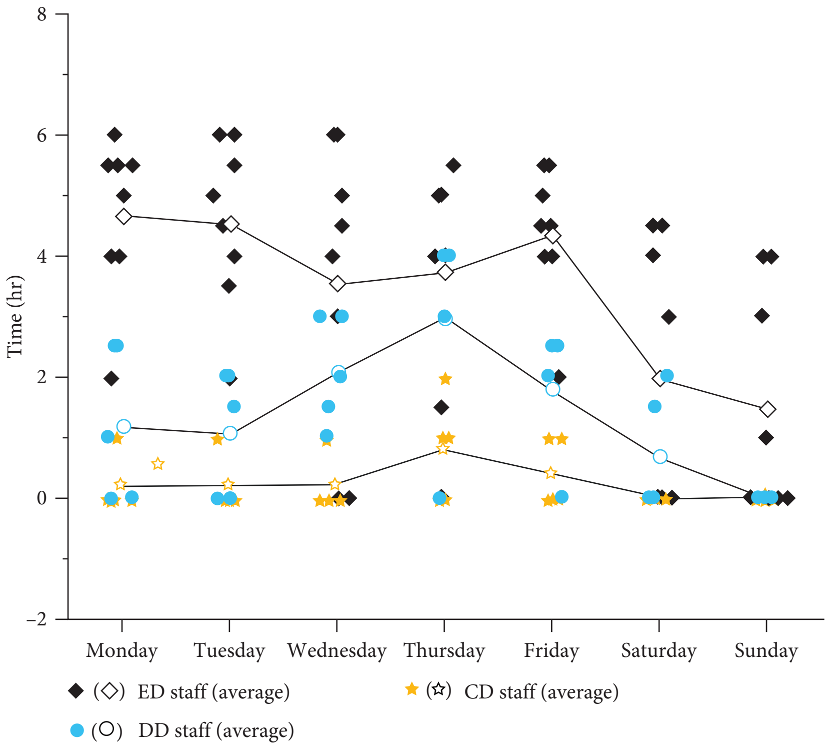

Figure 4: Time on site for each department during a week.

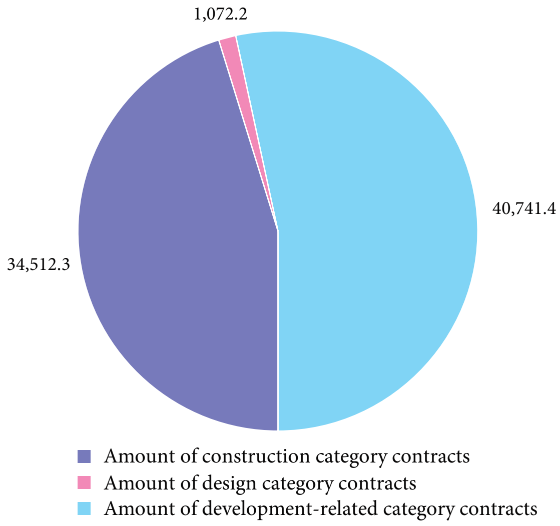

Figure 5: Contract amount under each directory. Unit: 10^4 CNY.

$$\lambda_{\max} = \frac{1}{n} \sum_{i=1}^{n} \frac{(AW)_i}{W_i}. \tag{3}$$

Following the calculation of the corresponding feature roots and weights based on the above formula, the next step involves detecting the consistency index CI using the following methods:

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n - 1}, \tag{4}$$

Table 1: Judgment matrix of time/cost of each department.

DP	ET	EC	DT	DC	CT	CC
ET	1	1.85	5.25	6.80	7.14	2.84
EC	0.54	1	4.88	4.76	2.19	3.47
DT	0.19	0.21	1	2.89	3.25	2.08
DC	0.15	0.21	0.35	1	1.71	1.28
CT	0.14	0.46	0.31	0.59	1	1.38
CC	0.35	0.29	0.48	0.78	0.73	1

where n is the matrix order (here $n = 6$), when $n = 6$, $\mathrm{RI} = 1.25$:

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}}. \tag{5}$$

The results using AHP can then be output in Table 2.

The weight values obtained from the aforementioned method can be utilized within the subsequent evaluation system to establish a comprehensive multidimensional evaluation method predicated on the dimensions of time and cost.

The results show that ET has a weight of 41.53%, EC has a weight of 26.70%, DT has a weight of 11.95%, DC has a weight of 6.69%, CT has a weight of 6.27%, and CC has a weight of 6.87%. The consistency test resulted in the parameter $\mathrm{CR} = 0.08 < 0.1$, which passed the consistency test, marking the data as correctly calculated and feasible.

In the context of AHP analysis, sensitivity analysis plays a crucial role in examining how various input parameters

Table 2: Results of analytic hierarchy process.

Element	Eigenvector	Weight value (%)	Maximum eigenvalue	CI value
ET	3.32	41.53	6.50	0.1
EC	2.14	26.70		
DT	0.96	11.95		
DC	0.54	6.69		
CT	0.50	6.27		
CC	0.55	6.87		

influence weight outcomes [46]. In this study, the square root method weights, utilized as factors in nonlinear combinations were employed. The author opted to conduct sensitivity analysis by adjusting the element with the largest value or the largest reciprocal value in each row (denoted as $W\sim$) within the range of 0–9 (or 0–1). This allowed for the observation of how these variations affected the evaluations of the six criteria. In this case, the graphical interpretation of functions of $W\sim$ is shown in Figure 6.

As shown from the figure, when the adjusted variable increases, the resulting $W\sim$ is increased. It can be found that when the value of elements in the judgment matrix is larger, its variation amplitude has little influence on the weight of other results; when the value of elements in the judgment matrix is smaller, its variation amplitude has a significant influence on the weight of other results. This is also why the six subcriteria should be investigated in detail: different factor weights may have significant changes to the DP.

2.3. Evaluation of Project Decisions. Fuzzy set theory was initially introduced by Zadeh [47] to tackle uncertainty stemming from imprecision or vagueness. The fuzzy comprehensive evaluation method is a comprehensive evaluation approach grounded in the principles of fuzzy mathematics. This method facilitates the conversion of qualitative evaluations into quantitative assessments by leveraging the principles of fuzzy mathematics, thereby enabling an overarching evaluation of entities or objects influenced by multiple factors. Notably, several notable practical instances have emerged concerning the integrated application of the AHP and fuzzy theory across diverse domains [48, 49]. The fuzzy set theory is the affiliation theory of fuzzy mathematics converting qualitative evaluation into quantitative evaluation, using fuzzy mathematics to make an overall evaluation of something or an object [50] that is subject to multiple factors. It is more appropriate for nondeterministic problems such as determining the reasons for improving management efficiency, and it also has the mathematical properties of calculating weights and priorities as well as well-validated. The advantages of these two methods are combined to determine the mentioned six subcriteria layer weights by the AHP method, and then evaluate the influencing factors by multilevel fuzzy comprehensive evaluation method, and finally, the two evaluation weights are combined and assigned to determine the ranking of influencing factors in each criterion.

The factor collection process for assessing the impact of BIM technology on decision-making within EPC projects was carried out meticulously. To capture the intricacies of BIM-related decisions, a comprehensive approach involving triangulation of data sources was employed. This included conducting field interviews (FI) with developer project management staff involved in the decision-making processes of BIM implementation across seven representative EPC projects. These interviews were designed to gain first-hand insights into the practical challenges, benefits, and considerations associated with BIM usage. To supplement the qualitative data obtained through interviews, the study also drew upon secondary sources. Literature reviews were conducted to consolidate and compare findings from previous studies that had explored similar themes. This allowed for the identification of common trends and patterns in the literature, ensuring that the research was grounded in existing knowledge and theory. Furthermore, project documents such as reports, meeting minutes, and other records related to BIM implementation were analyzed. These documents provided a historical perspective on decision-making processes and helped to validate the information gathered through interviews. However, it is imperative to acknowledge potential biases inherent in self-reported data; participants might have been inclined to present their experiences in a positive light or align their responses with perceived expectations. To mitigate this, the triangulation of data sources was employed to cross-validate information, enhancing the reliability of the findings. Through this approach, the paper consolidates seven overarching factors and eighteen subfactors, and Table 3 provides specific factors and their detailed explanations.

The first step in using the fuzzy evaluation method is to determine the set of factors. Factor set is a general set U composed of various factors affecting the evaluation object as elements, and the primary factor (PF) in the above table then constitutes the factor set U_i. In contrast to the usual weighting methods such as entropy weighting, the weighting of the factor set is determined by applying the combined evaluation of time and cost (ET, EC, DT, DC, CT, CC), as mentioned in the above section. This approach takes into account both the time and cost factors and their relative importance in the decision-making process. By considering the specific requirements and constraints of the project, a comprehensive evaluation is conducted to assign appropriate weights to each factor in the set. This ensures a more accurate and balanced representation of the factors' significance and their impact on the overall decision. According to the above method, a set of weights A can be obtained. Specific schemas are as follows:

(1) Determine which subcriteria each secondary factor (SF) is primarily influenced by and assign the corresponding

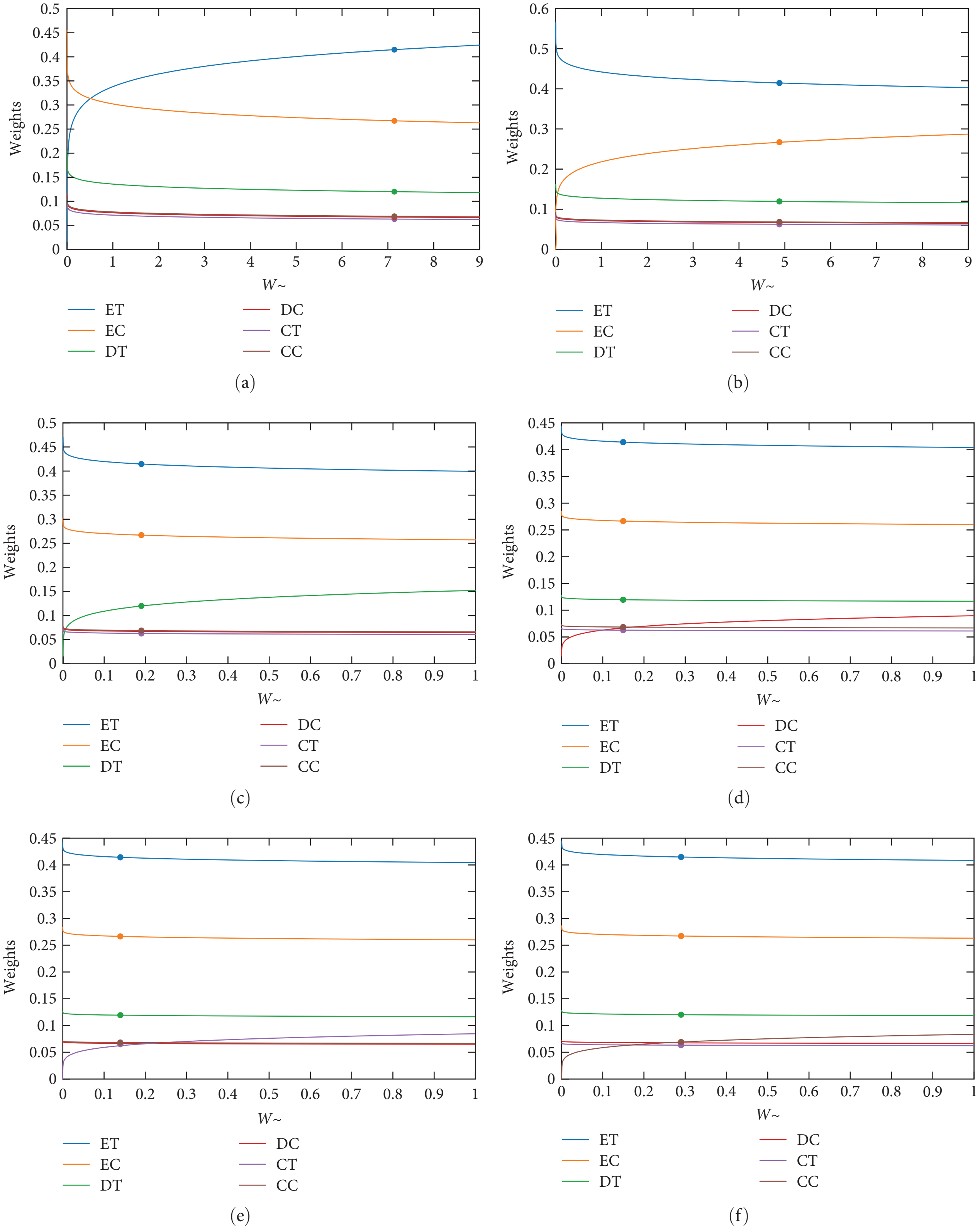

Figure 6: Sensitivity analysis: (a) ET judgment row, (b) EC judgment row, (c) DT judgment row, (d) DC judgment row, (e) CT judgment row, and (f) CC judgment row.

Table 3: Factors affecting decision analysis of construction developers.

Primary factor	Secondary factor	Detailed explanation
Maturity of BIM technology	SF1 : technical feasibility (FI)	Assessing the maturity of BIM technology draws from industry reports, academic research, software providers, and case studies, while evaluating its technical feasibility involves analyzing software documentation, industry standards, research papers, and engaging with professional networks
	SF2 : industry acceptance (FI)	Industry acceptance in the decision analysis of construction developers is substantiated through a synthesis of scholarly literature, industry reports, and empirical studies, supplemented by case studies and successful experiences sourced from peer-reviewed journals, industry forums, and standards
	SF3 : market supply (FI)	Market supply, crucial in decision analysis for construction developers, is meticulously evaluated through a comprehensive scrutiny of BIM software and service providers, encompassing their technical support infrastructure and training provisions, with insights sourced from industry reports, vendor assessments, and firsthand experiences documented in scholarly literature and professional forums
Investment and return	SF4 : cost analysis (FI)	Involving a thorough examination of the financial outlays associated with the adoption of BIM technology, encompassing procurement expenses for software and hardware, costs related to training programs, and implementation expenditures, with data sourced from industry benchmarks, financial reports of projects
	SF5 : benefit assessment [51]	Entails a multifaceted analysis of anticipated returns, including reductions in project duration, mitigation of errors and conflicts, enhancement of engineering quality, and visualization capabilities, drawing insights from empirical studies, comparative analyses
Project management efficiency goals	SF6 : schedule control (FI)	Evaluating the influence of BIM technology on project schedule planning, control, and progress tracking is pivotal in setting efficiency goals for project management
	SF7 : quality management (FI)	Considering the application of BIM technology in design coordination, clash detection, and quality control which has progressed from initial implementation by industry pioneers to a sophisticated standard practice
	SF8 : resource optimization (FI)	Analyzing potential benefits of BIM technology in material and resource management, construction planning, and supply chain coordination
Internal resources and capabilities	SF9 : technical team proficiency (FI)	Evaluating the internal team's proficiency in BIM technology, training needs, and capability enhancement plans. The aim is organizations can experience increased productivity, cost savings, and sustainability in their construction operations by leveraging the power of BIM
	SF10 : software and hardware infrastructure [52]	Assessing the readiness of software and hardware infrastructure for BIM implementation involves gathering specifications from hardware manufacturers and software providers, evaluating existing infrastructure, and planning for scalability and risk mitigation
Supply chain collaboration	SF11 : designer capability (FI)	Assessing the capability of the design team in utilizing BIM technology involves evaluating their proficiency, experience, training records, project history, and adherence to industry standards to ensure effective coordination in delivering design models
	SF12 : contractor acceptance [53]	Understanding contractor acceptance of BIM technology involves assessing qualifications, industry reputation, client feedback, and contractual agreements, while ensuring effective communication, training, trials, regular meetings, and quality assurance processes to facilitate data exchange and coordination during construction
	SF13 : supplier collaboration (FI)	Evaluating supplier collaboration involves assessing data-sharing capabilities and integration methods to optimize material and equipment supply management processes
Risk and uncertainty	SF14 : technology integration risk (FI)	Assessing technology integration risk entails evaluating the complexity and potential challenges associated with integrating BIM technology with existing systems, including considerations of data format compatibility and interface issues
	SF15 : data integrity and quality (FI)	Ensuring data integrity and quality involves prioritizing the accuracy and reliability of BIM model data through meticulous data collection, regular updates, and rigorous verification processes
	SF16 : data security risk (FI)	Evaluating data security risk involves analyzing the security requirements and implementing measures to safeguard BIM data, protecting project information from unauthorized access and potential leakage
Organizational culture and change management	SF17 : organizational culture (FI)	Assessing organizational culture involves evaluating the acceptance of and potential cultural changes needed within the organization regarding BIM technology, including the development of training and education plans to support adoption
	SF18 : change management [54]	Developing effective change management strategies for BIM adoption and implementing a structured development process encompassing stakeholder analysis, communication plans, training programs, support mechanisms, incentive structures, pilot projects, feedback mechanisms, and continuous improvement

Table 4: Determination of the weights of the factor set.

Factor	SF1	SF2	SF3	SF4	SF5	SF6	SF7	SF8	SF9	SF10
Primary influence	DC	DT	CT	CT	CT	ET	DC	CC	DT	ET
Weight	6.69	11.95	6.27	6.27	6.27	41.53	6.69	6.87	11.95	41.53
W_i	8.30		6.27			18.36			26.74	
W_u	7%		6%			16%			24%	

Factor	SF11	SF12	SF13	SF14	SF15	SF16	SF17	SF18
Primary influence	CT	DT	DC	DT	DT	DC	ET	EC
Weight	6.27	11.95	6.69	11.95	11.95	6.69	41.53	26.70
W_i	8.30			10.20			34.12	
W_u	7%			9%			30%	

Weight set A can be obtained as $A = \{7\%, 6\%, 16\%, 24\%, 7\%, 9\%, 30\%\}$.

Table 5: Fuzzy integrated judgment matrix.

Primary factor	Effective	Slightly effective	Average	Less effective	Completely ineffective
Maturity of BIM technology	0.38	0.31	0.23	0.08	0.00
Investment and return	0.15	0.31	0.15	0.23	0.15
Project management efficiency goals	0.46	0.31	0.08	0.15	0.00
Internal resources and capabilities	0.15	0.31	0.31	0.15	0.08
Supply chain collaboration	0.31	0.38	0.23	0.00	0.08
Risk and uncertainty	0.23	0.15	0.23	0.15	0.23
Organizational culture and change management	0.00	0.15	0.38	0.31	0.15

weights. Using Equation (6), the initial weights W_i of the primary factor are calculated:

$$W_i = \sum_{j=1}^{n} \frac{1}{n} \times \text{weight}_{\text{subcriteria}}, \tag{6}$$

where j is the number of secondary factors for each primary factor.

(2) Using the linear scaling method for W_i in order to obtain the ultimate weights W_u:

$$W_{u_{u\in[1,7]}} = \frac{W_i}{\sum_{i=1}^{7} W_i} \times 100\%. \tag{7}$$

The detailed process results and W_u are shown in Table 4.

The second phase is to determine the set of comments, which is the set V of the possible results of the evaluator on the evaluation object, and the comprehensive evaluation of a factor affecting the DP can be divided into five levels: $V=$ (effective, slightly effective, average, less effective, and completely ineffective). The results are obtained through interviews conducted with staff of the management team (excluding the one general manager) affiliated with projects. Given the existence of m evaluation indexes, each factor undergoes m evaluations. The n single-factor evaluation sets (R_1, R_2, …, R_n) are arranged as rows to construct the matrix $R_{n\times m}$, commonly defined as the fuzzy comprehensive evaluation matrix. In the present study, a total of seven factors were considered, and each factor was evaluated at five levels. Therefore, the dimensions of the evaluation matrix are seven rows and five columns, as shown in Table 5. The present study elicited a fuzzy integrated judgment matrix is shown in Table 5.

Similarly, an evaluation matrix $R_{7\times 5}$ consisting of pure numbers can be obtained from Table 5. The evaluation result B can be obtained by the operation of weight set A and evaluation matrix R (Equation (9)):

$$B = A \times R = \{w_1, w_2, \cdots w_7\} \times \begin{bmatrix} r_{11} & \cdots & r_{15} \\ \vdots & \ddots & \vdots \\ r_{71} & \cdots & r_{75} \end{bmatrix}. \tag{8}$$

The common model operators used in the calculation are the following four types:

1. Principal determination type: M (Λ, V), the main factor determines.
2. Principal highlight type: M (×, V), prominent main factor.
3. Minimum with bounded type: M (Λ, +), unbalanced average.
4. Weighted average type: M (×, +), weighted average.

If it is necessary to take into account the weight of each element and the result should reflect the overall characteristics of the evaluated object, the model operator (4), which is the weighted average type, can better analyze the results of the whole system [55]. In this study, the weighted average type M (×, +) operator is utilized.

Table 6: Evaluation result B.

	Effective	Slightly effective	Average	Less effective	Completely ineffective
Normalized membership	0.191	0.253	0.267	0.189	0.101

3. Results and Optimization Strategy

Initially, using the evaluation index weight vector A, derived from custom weights, a 7×5 weight judgment matrix R is constructed. The outcomes are presented in Table 6, displaying the membership matrix results following the normalization process. Membership normalization is the result of normalizing the membership, the membership normalization of all the evaluations sums up to 1, as previously mentioned. Through subsequent analysis, the resulting rubric set affiliations are determined as follows: 0.191, 0.253, 0.267, 0.189, and 0.101.

Table 6 illustrates the fuzzy composite evaluation for seven indicators (maturity of BIM technology, investment and return, project management efficiency goals, internal resources and capabilities, supply chain collaboration, risk and uncertainty, and organizational culture and change management). The evaluation involves five ratings: effective, slightly effective, average, less effective, and completely ineffective.

Consequently, it can be deduced that the rubric set with the highest general weight is obtained, enabling the determination of the maximum affiliation law within the set. Ultimately, the comprehensive multidimensional evaluation outcome is "Average." The evaluation results suggest that the use of BIM technology in EPC projects may not contribute much to decision-making by the developer's management staff.

3.1. Optimization Strategy. Based on the preceding sections' discussions, the researcher has established a weight distribution for each sector based on the dimensions of time and cost, with ET assigned the largest weight. Subsequently, when the primary factors (PF) underwent processing using the linear scaling method, it was observed that the two key factors, internal resources and capabilities, and organizational culture and change management, carried the highest weights. Ultimately, the findings in Tables 5 and 6 suggest that internal resources and capabilities, as well as organizational culture and change management, do not significantly impact project decisions according to the perceptions of construction developers.

There have been projects based on BIM technology that have an expert evaluation system for performance, but the optimization system for decision-making has not been studied much. According to the previously constructed evaluation methodology and results, it can be inferred that the current application of BIM technology in EPC projects falls short of the expected optimal solution for project developer management staff as expected. To address this, the optimization strategy was implemented in one of the projects with the smallest number of management staff. Meanwhile, both the general contractor and the developer held an equity stake in the project. This project's characteristics made the implementation of the strategy relatively straightforward and facilitated the process. A recommendation was made to the general manager to formulate the decision process depicted in Figure 7. This initiative aimed to enhance the efficiency of management decision-making for one of the projects based on the aforementioned findings.

In the above management decision process, the two most important steps are choosing the path to enhance efficiency and determining whether it works. In this decision analysis, BIM model usage (BMU), model clash rate (MCR), project schedule compliance (PSC), resource utilization rate (RUR), and project risk identification (PRI) were used as the five indicators to judge the effectiveness. Based on this, a matrix of judgment indicators X_{nm} can be constructed, where the rows are judgment indicators and the columns are path to enhance efficiency.

$$X_{nm} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n1} & \cdots & x_{nm} \end{bmatrix}, \tag{9}$$

where X_{nm} is the scoring of the judgment indicators, and $n \in [1,6]$, m $\in [1,5]$.

Each judgment indicator is calculated as follows:

(1) BIM model usage (BMU):

$$\frac{\text{BIM model usage time}}{\text{Total drawing usage time}} \times 100\%. \tag{10}$$

(2) Model clash rate (MCR):

$$\frac{\text{Resolved clashes}}{\text{Changes due to clashes}} \times 100\%. \tag{11}$$

(3) Project schedule compliance (PSC):

$$\frac{\text{Planned schedule} - \text{actual schedule}}{\text{Planned schedule}} \times 100\%. \tag{12}$$

(4) Resource utilization rate (RUR):

$$\frac{\text{Actual resource usage}}{\text{Planned resource usage}} \times 100\%. \tag{13}$$

(5) Project risk identification (PRI):

$$\frac{\text{Actual number of risk events occurred}}{\text{Preidentified risks}} \times 100\%. \tag{14}$$

The best and worst options should be the objectively best and worst possible options. The best and worst solutions

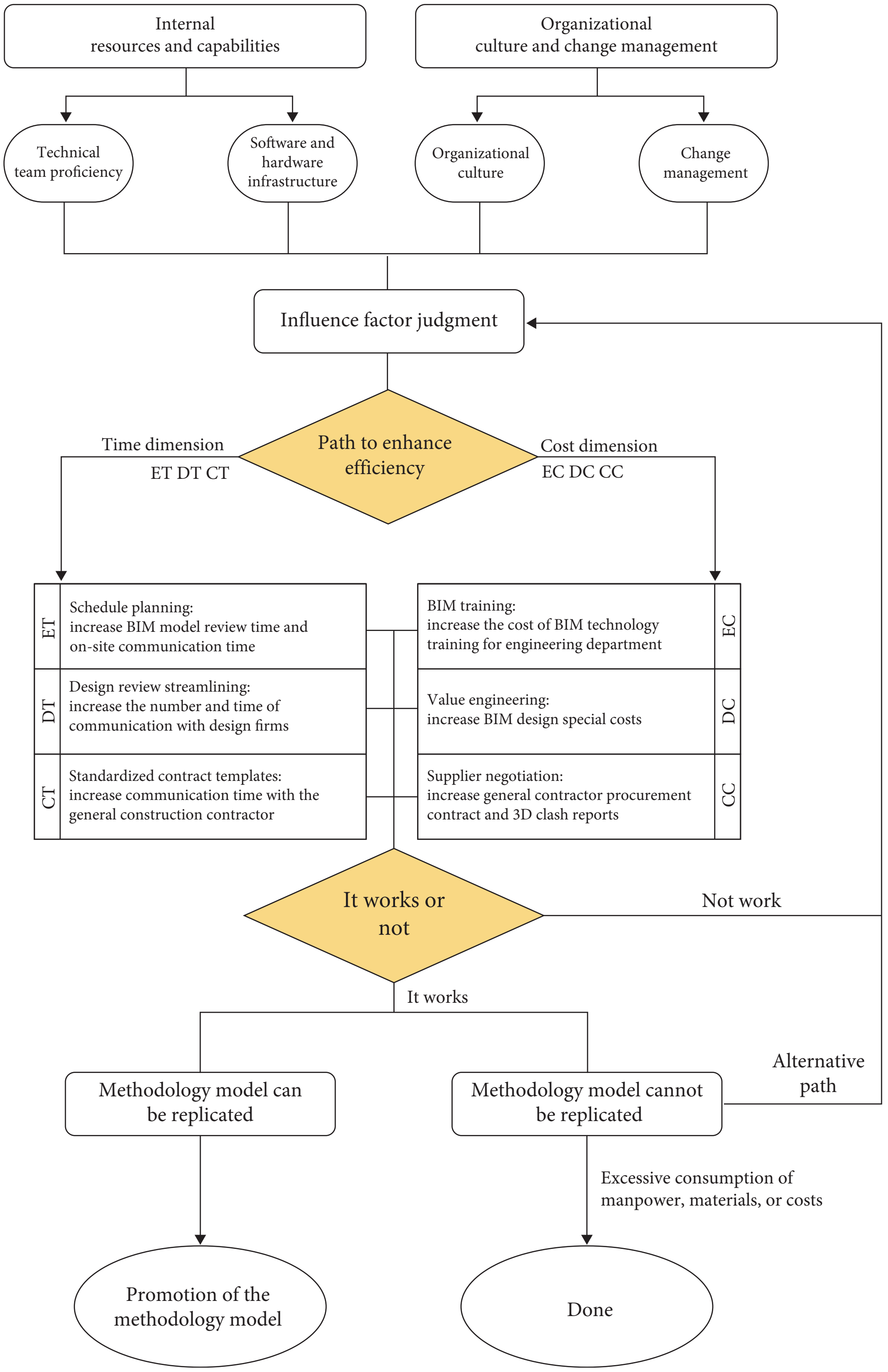

Figure 7: Management decision efficiency improvement decision process.

here should be derived from the nature of the system, and from Equations (10), (11), (12), (13), and (14). The best solution B and worst solution W can be written in the form of vectors as follows:

$$B = \{1, 1, 0, 1, 1\},$$
$$W = \{0, 0, -1, 2, 2\}.$$

The matrix X_{nm} can be extended by adding the vectors B and W to obtain the matrix X according to the above discussion:

Table 7: Evaluation result B after postevaluation.

	Effective	Slightly effective	Average	Less effective	Completely ineffective
Normalized membership	0.321	0.255	0.199	0.164	0.062

$$X = \begin{bmatrix} x_{11} & x_{12} & x_{13} & x_{14} & x_{15} \\ x_{11} & x_{22} & x_{23} & x_{24} & x_{25} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_{n1} & x_{n2} & x_{n3} & x_{n4} & x_{n5} \\ 1 & 1 & 0 & 1 & 1 \\ 0 & 0 & -1 & 2 & 2 \end{bmatrix}. \quad (15)$$

At this juncture, the calculation of the distance between the best and the worst solutions is required, considering the disparity between the corresponding columns and the values 1 and 0 for different lifting paths. The primary objective is to identify the path that exhibits the shortest distance to the optimal solution and the longest distance to the worst solution.

Following an initial evaluation of the project structure and its feasibility by the author and the project staff, and considering the characteristics of the four SFs, a decision was reached to pursue optimization in the ET and CC paths. For the ET path, the specific optimization measures include daily technical collaboration with the design department and regular on-site communication with the construction general contractor, lasting 15 days. Regarding the CC path, the specific optimization measures entail increasing the BIM special cost for material procurement by the general contractor and proactively conducting model collision detection before material preparation to prevent on-site rework or secondary processing. These measures are expected to be implemented continuously for a duration of 30 days.

After a period of approximately 2 months, which involved overcoming initial challenges and making adjustments to the management strategy, the outcomes of the two paths were summarized to obtain matrix X:

$$X = \begin{bmatrix} 0.3 & 0.9 & 0 & 1.2 & 1.1 \\ 0.1 & 0.6 & 0.2 & 1.1 & 1 \\ 1 & 1 & 0 & 1 & 1 \\ 0 & 0 & -1 & 2 & 2 \end{bmatrix}. \quad (16)$$

The simple matrix R of X after simplification by Gauss–Jordan elimination is as follows:

$$R = \begin{bmatrix} 1 & 0 & 0 & 0 & 0.1538 \\ 0 & 1 & 0 & 0 & -0.1282 \\ 0 & 0 & 1 & 0 & -0.0513 \\ 0 & 0 & 0 & 1 & 0.9744 \end{bmatrix}. \quad (17)$$

Upon examining the transformed matrix R after the elementary row transformation, we observe that the absolute value of the last column in the third row (representing the best solution) is 0.0513. This indicates that the corresponding optimization path approaches the best solution. Conversely, the absolute value of the last column in the fourth row (representing the worst solution) is 0.9744, suggesting that this particular optimization path is significantly distant from the worst solution. Following the time optimization of the ET path, the competence of the immediate managers at the project site in terms of technical team proficiency was reinforced through extensive departmental meetings. This resulted in a tacit understanding of the organizational culture, facilitated by the collaborative efforts of multiple departments. Simultaneously, the infusion of funds into the CC path elevated the cooperation among project management, material suppliers, and other hardware and software entities to a new level. Furthermore, the early-stage implementation of BIM technology supported the effective enhancement of change management processes.

3.2. Postevaluation. After conducting a resurvey using the methodology outlined, the subjective decision-making of the total 13 members of the management team was analyzed. The comprehensive multidimensional evaluation results of the project decision-making, as depicted in Table 7, were obtained through this process.

By comparing Tables 6 and 7, it becomes clear that the subjective evaluation of project decision-making by management staff has significantly improved after the implementation of optimization measures. At the same time, due to the BIM-based management measures optimization, the comprehensive multidimensional evaluation outcome to DP of the project management staff is changed to "Effective." This observation suggests that both of the aforementioned enhancement paths are feasible based on the results achieved. Meanwhile, when comparing the traditional key performance indicator (KPI) assessment method used before, all 13 project management staff unanimously expressed that the method employed under the optimized process was more objective and humane.

Upon conducting a postevaluation of the ET and CC paths by the project management team, it has become abundantly clear just how crucial the ET enhancement path is. Notably, the majority of stakeholders, including the project's general manager, strongly favor adopting the ET enhancement path for future optimization. This preference is rooted in the fact that the specific improvement measures for ET can be implemented without incurring additional costs. In contrast, the decision to allocate extra funds to BIM-related activities has led to the signing of ancillary contracts totaling 684,500 CNY on top of existing commitments. Such an expenditure is clearly untenable given our overarching goal of cost reduction and efficiency enhancement. Consequently, in our final phase in refining the decision-making process, we unequivocally endorse the ET path as a replicable model for achieving these objectives.

4. Discussion

This study aimed at improving decision-making efficiency in engineering, procurement, and construction (EPC) projects through the application of BIM technology, leveraging a comprehensive evaluation method that integrates the AHP and fuzzy comprehensive evaluation. A key observation was the development of judgment indicators and an evaluation matrix tailored specifically to BIM-assisted general construction projects, providing a robust platform for decision analysis by project management staff. Contrary to initial expectations of universally positive attitudes toward BIM's impact on decision-making efficiency, the empirical investigation across seven EPC projects revealed mixed responses. Nevertheless, the study successfully demonstrated the viability of the proposed model in enhancing decision-making efficiency in at least one of the projects, underscoring its potential practical utility. This outcome contributes to the body of knowledge by introducing a multidimensional approach to BIM-enabled project management, which fills a gap in understanding how to effectively assess and optimize BIM's role in construction decision-making.

Regarding the comparison with prior studies, our work aligns with efforts by researchers like Guo et al. [19] and Sacks et al. [20], who have explored BIM implementation in infrastructure and advocated for its integration with advanced technologies. However, this study distinguishes itself by developing a unique BIM-integrated decision-making framework, offering a structured methodology for evaluating BIM's impact on management efficiency. It thereby sets a new benchmark for BIM adoption strategies and workflow optimization.

The main contribution of the study can be summarized as following four points:

(1) Introduces a multidimensional comprehensive evaluation method combining AHP and fuzzy comprehensive evaluation, tailored for general construction projects using BIM technology, which helps to facilitate decision analysis for project managers.

(2) Demonstrates how the methodology can improve the decision-making efficiency of construction developer management, focusing on the practical results of the efficiency improvement strategy based on the judgmental indicator method.

(3) Develop a unique framework for integrating BIM technology into the decision-making process, setting a new benchmark for technology adoption and workflow optimization in the construction industry.

(4) Provide insights and guidelines for future research and practice in the field of construction management, particularly with regard to technology integration and strategic decision-making processes.

5. Conclusion

The study aimed to enhance decision-making in EPC projects by examining the use of BIM technology among project management staff. Despite initial expectations of positive outcomes, a survey among management staff from seven projects, using the AHP and the fuzzy evaluation comprehensive method, revealed a generally unfavorable attitude toward the decision-making efficiency of BIM in EPC projects. The study involved creating judgment indicators and a matrix for evaluation. A new model incorporating these indicators was developed, offering paths to improve management decision-making efficiency. This approach showed effectiveness in one of the projects, indicating its potential utility. The study acknowledges that different company backgrounds and project types can influence the decision-making process. Time and cost were used as primary dimensions for adjustments. The limitations include a small sample size and a lack of consideration for collaboration and coordination among different construction entities due to time and information constraints. At last, the authors suggest expanding the sample size for more diverse insights and exploring the level of collaboration and coordination among different suppliers or EPC contractors, as their proficiency in BIM and organizational capabilities are crucial.

In summary, the study provides a comprehensive evaluation method and improvement path for BIM technology in EPC projects, highlighting its potential for enhancing decision-making efficiency, with an acknowledgment of external influences and limitations. The findings also pave the way for further research in the integration of technology in construction project management.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper

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