Hindawi
Mathematical Problems in Engineering
Volume 2024, Article ID 8893201, 17 pages
https://doi.org/10.1155/2024/8893201

Research Article

Novel Probabilistic Approach for Quantification of Cost-Overruns Risk and Determination of Primary Causes

Tianyu Liu, Shen Zhang, and Xingyu Wang

Central-South Architectural Design Institute Co., Ltd., Wuhan 430071, China

Correspondence should be addressed to Shen Zhang; csadi_zhangs@csadi.cn

Received 16 October 2023; Revised 29 December 2023; Accepted 3 January 2024; Published 19 January 2024

Academic Editor: Serdar Ulubeyli

Cost management is a crucial component of construction project management, which assumes an increasingly critical role in modern large-scale projects. Ideally, cost management is achieved through a comparison between the current cost and the predetermined cost schedule. However, in real-world projects, it is often difficult to consistently obtain accurate costs for each cost item throughout the project life cycle and to predict the probability of various risk occurrences. To address this challenge, we propose a novel building information modeling- (BIM-) based algorithm to quantify the risk of cost overruns and cost deviation; and identify the primary causes without a detailed cost breakdown. The role of BIM in our approach is to automatically extract precise quantitative information that we can use to calculate the probability density function of the current cost and the expected total cost and eventually combine reliability analysis to provide the risk probability. The numerical experiment demonstrates that this algorithm can estimate the probability of cost overruns and cost deviation, and identify the primary cause of deviation. Additionally, the sensitivity requirements for cost management can be adjusted by adjusting the parameters, indicating its potential to meet multiple requirements in the different projects. The proposed algorithm provides a method for detecting the current risk of cost overruns and cost deviation, as well as identifying the primary cause of deviation, which is of potential value in the practical applications.

1. Introduction

Construction cost management plays a crucial role in facilitating project success within predetermined budget constraints. However, the complex and uncertain nature of construction projects poses great challenges for project managers in effectively managing costs [1–3]. To ensure the smooth execution of the project, it is imperative to prioritize cost management, with a particular focus on assessing the risk of cost overruns. Currently, numerous cost-management techniques exist, ranging from the traditional bill of quantity (BOQ) to the recently popularized building information modeling- (BIM-) based approach [4–6]. While BOQ, activity-based costing (ABC), and the earned value method (EVM) offer simplicity and clarity, they also suffer from limitations such as time-consuming calculations, proneness to errors, and limited accuracy [7]. Given BIM's inherent advantages of intuitive representation and precision, it has become a cornerstone of digitalization in the construction field. Furthermore, the integration of 5D BIM into practice represents a promising advancement, offering a comprehensive and integrated platform to enhance cost-management practices [8]. In contrast to traditional methods that primarily focus on cost estimation and control, 5D BIM integrates costing data with existing 3D models and project schedules, thus enabling thorough cost control and evaluation throughout the entire project life cycle. In this article, we propose a novel probabilistic approach for quantification of cost-overruns risk utilizing a 5D BIM framework, enhancing decision-making efficacy among project management. This method capitalizes on the accurate quantification of materials and the detailed scheduling afforded by 5D BIM to determine the likelihood of cost overruns and the extent of cost deviations during the entire construction timeline. It obviates the need for reliance on labor-intensive and error-prone detailed cost analysis, thereby facilitating a more intuitive visual representation of the current financial status for the project managers.

2. Literature Review

Accurate cost estimation and effective cost monitoring and control are essential elements for achieving success in the construction projects. To achieve this, project managers must choose a reliable cost-estimating system to establish accurate budgets and develop comprehensive financial management plans. However, according to Jrade's research [9], the level of accuracy in cost estimation depends on factors such as the chosen methodology, the availability of cost data, and the degree of project definition. In traditional construction projects, obtaining cost statistics is often cumbersome, time-consuming, and prone to errors as it requires manual counting and calculation of the engineering quantities. Consequently, this inefficient and inaccurate estimation makes it difficult to implement cost control [1, 2]. In the next sections, we delineate cost-management methodologies with a comparative analysis between those integrated with BIM and those devoid of BIM. Furthermore, we will explicate the concept of 5D BIM, examine the predominant challenges encountered in contemporary research, and elucidate our proposed method.

2.1. Non-BIM-Based Cost Management. In the domain of the construction industry, there exist multiple cost-management strategies that are not predicated on the integration of BIM. These range from the conventional BOQ to the more contemporary ABC, as well as the EVM. Such methodologies primarily rely upon the rudimentary computation of cost items and are inherently deficient in their capacity to provide an intuitive representation of the risk of cost overruns and cost deviation. BOQ is an instrumental document within the construction sector, offering a comprehensive enumeration of materials, labor, and the projected volumes pertinent to a construction project. It is instrumental in underpinning the processes of cost estimation, risk mitigation, and financial oversight, thereby ensuring the project's completion within the budget and in alignment with the project plan [10]. Characterized by a detailed inventory of cost elements compiled at the project's inception, the BOQ confers a strategic advantage for construction entities in the realm of investment control over the project [4]. ABC represents a costing methodology that involves identifying activities within an organization and allocating the cost of each activity resource to all products and services based on their actual consumption. ABC assigns costs to activities according to their utilization of resources and has been shown to significantly enhance the quality of cost management, particularly in the realm of construction [11]. This method diverges notably from other costing techniques, particularly in the manner in which indirect cost units are assigned to activities based on their actual causation, and in the allocation of activities to specific cost items based on the intensity of their consumption. Moreover, this approach empowers decision-makers to pinpoint precise cost items and determine strategies for their effective management [12]. The EVM constitutes a project management technique designed to exercise control over project cost performance and duration, enabling the identification of trends during execution and facilitating timely corrective actions by the project manager. Notably applied in construction, it underscores the regulation of project cost performance and duration, thus finding widespread use in monitoring and governing project costs and schedules within construction industry [13]. The EVM confers several advantages in project management, encompassing enhanced cost and schedule control, improved risk management, real-time project monitoring, optimized resource management, and seamless integration with the other project management techniques [13, 14]. As a non-BIM-based cost-management method, the EVM demonstrates superior performance and enjoys extensive international adoption. However, traditional EVM may place greater emphasis on analyzing and forecasting the overall project, potentially neglecting the performance of internal activities, leading to appraisal conclusions that diverge from the actual case [15]. It is pertinent to note that while these methods are not predicated on BIM usage, they can be effectively amalgamated with BIM to achieve enhanced performance. Subsequently, the following section will expound upon the evolution of cost-management methods catalyzed by BIM.

2.2. BIM-Based Cost Management. As a digital method, BIM has many more precise measurements compared to the other traditional drawing-based cost-management methods, which is why BIM has been applied in the cost management in recent years. As stated by Eastman [16], the adoption of BIM results in enhanced constructability, reduced project cost, and shorter project duration. By utilizing the capabilities of BIM, particularly in conjunction with the Industry Foundation Classes (IFC) standards, construction models could be accurately defined and modeled, with each element possessing semantic attributes. BIM allows for the accurate capture and identification of relationships among different components and elements, thereby facilitating the rapid and precise calculation of the engineering quantities. A study conducted by Babatunde et al. [17] highlighted the necessity of BIM applications for quantity surveying and cost estimating, as evidenced by a comprehensive analysis of literature, pilot studies, and a questionnaire survey involving 73 participants from Nigeria, consisting of both BIM users and nonusers.

To attain efficiency and effectiveness in cost management in construction projects, the implementation of automatic high-precision quantities calculation within the BIM framework becomes imperative. To achieve this, Lawrence et al. [18] develope a new BIM-based estimating application named Innovaya. This application collects design information and associated BIM data, enabling automatic recalculation of assembly quantities in the event of design revisions. The revised assembly quantities are then semi-automatically updated and exported to spreadsheets or integrated with a chosen cost database for quantity calculation. Besides, they suggest updating estimations when estimate changes occur, allowing users to compare and reference estimates with BIM data and make informed decisions on the necessary updates.

Similarly, Abanda et al. [19] investigate the development of an ontology for cost estimation based on novel measurement rules. The authors utilize the Navisworks software to enable users to select quantification functions and access standardized measurement catalogs. By importing the proposed catalog, users can choose specific elements and estimate quantities accordingly. To evaluate the semantic effectiveness of the ontology, six experts in cost estimation are consulted, while the validation process involves the utilization of 4D BIM modeling and the Manchester OWL syntax validator.

2.3. 5D BIM in Construction Project. It is worth mentioning that both traditional methods and BIM-based cost-management methods have a common drawback, which is the neglect of the relationships between components, such as the need for engineering to proceed in a certain order. To address this issue, researchers have integrated the schedule and cost into traditional 3D BIM and proposed the concept of 5D BIM. Many research studies have underscored the theoretical and practical benefits of employing 5D BIM [20–23], including overall cost reduction and control, the ability to swiftly and flexibly estimate costs and formulate living cost plans, and the enhancement of cost-estimation precision and contract value savings. These encouraging advancements in existing construction practices have prompted considerable number of general contractors and industry professionals to actively consider and adopt 5D BIM, due to its immense potential to elevate cost management and project success. Reports from McGraw Hill [23] construction confirmed the widespread adoption and utilization of BIM within the construction industry.

However, project cost management involves more than just estimating costs; it utilizes cost information to effectively plan, monitor, and supervise costs. Research suggests that the utilization of 5D BIM that combines BIM calculation with a detailed construction schedule will result in a comprehensive cost plan for the project, improving accuracy and transparency, ensuring budget adherence, and achieving effective cost control. To enhance cost control in construction projects, Wang et al. [24] present a novel approach that integrates three-dimensional BIM objects with schedule and cost, leveraging BIM for data acquisition and storage. Through the utilization of a four-step model that incorporates BIM objects, construction progress curves are established while search criteria are defined to enable accurate identification of takeoff objects and extraction of quantities of cost items associated with each activity. The BIM system further enhances efficiency by employing keynote, assembly code, and family type catalog functions, facilitating the precise identification of cost items linked to individual objects and minimizing errors in manual typing. Consequently, their proposed model exhibits superior reliability and precision in extracting and allocating quantities to activities, thereby outperforming conventional control methodologies.

A similar study was conducted by Alrashed and Kantamaneni [25] in Saudi Arabia to develop and evaluate the application of 5D BIM in housing projects. They used a two-path analysis approach, surveying participants' opinions on house styles and creating a 5D BIM model to estimate construction costs. The researchers utilized ArchiCAD to develop 3D CAD models and transferred them to Vico software for material codes and unit rates. By automating calculations in Excel, they easily incorporated design changes and created the final bill of quantities. The study found that traditional cost-estimation methods using tools like Excel were less accurate compared to the new methods associated with 5D BIM, resulting in more precise cost estimates. Besides, the introduction of the proposed 5D BIM approach also led to significant cost reductions by minimizing material waste and time clashes during construction.

Such potential benefit of using 5D BIM for more efficient and precise cost control is also explored in the study by Vigneault et al. [26]. The researchers aim to develop an innovative framework for 5D BIM solutions in the construction cost management. To evaluate the available 5D BIM solutions, a systematic review approach was employed. Additionally, interviews with industry experts were conducted to validate and provide feedback on the research findings. The study analyzed 18 software or web solutions against five-key areas of cost-management practices. Overall, the research contributes to enhancing understanding and knowledge of the current and future cost-management requirements in the digital working environment, utilizing the available 5D BIM solutions.

To enhance the integration of 5D BIM and quantity surveying practices, the study conducted by Baldrich Aragó et al. [27] tries to explore the deployment of BIM within the architecture, engineering, and construction (AEC) sector in Spain and its subsequent impact on quantity surveying practices. Employing a combination of literature review and qualitative analysis based on four case studies, the research aims to identify the key aspects of new processes, roles, and skills required by quantity surveyors in this BIM methodology. The collected information was qualitatively analyzed after coding from different sources. The research findings highlight the importance of a comprehensive database and all available information for the quality of quantity takeoff and project cost estimation in a 3D model. The findings also introduce a new role for quantity surveyors as cross-disciplinary professionals to improve the process.

In addition to addressing cost control and engineering quantity surveying, the study conducted by Amin Ranjbar et al. [28] also directs attention toward cash flow management within the construction industry, which remains a challenge for contractors. The researchers recognize the importance of this issue and aim to offer a simple BIM-based theoretically sound framework. The proposed framework is designed to accurately estimate project cash flow, considering payment patterns for materials, equipment, human resources, and subcontractors, as well as contract-related attributes. Additionally, it assesses the impact of risk factors on cash flow. The study follows a methodological approach of developing a proof of concept, using a case project in Iran to validate the framework's practicality. The findings contribute to the research community by providing theoretical foundations and logical procedures for a BIM-enabled cash flow management framework, while also offering practical value for contractors in predicting cash flows and making informed decisions in the construction projects.

Moreover, the utilization of 5D BIM has also emerged as a potential solution for enhancing construction duration and cost optimization within the construction industry. A comprehensive research conducted by He et al. [29] has outlined the combination of genetic algorithm (GA) and BIM to overcome the prevailing limitations in the current methods employed for construction period and cost-optimization analysis. By analyzing the characteristics of changing construction periods and costs, the study improves the genetic mechanism and data processing method in GA. BIM technology is then integrated with GA to test the feasibility of the model in real engineering projects. The findings demonstrate that this new method is reasonable and effective in addressing the complexity of period and cost optimization. GA accelerates the optimization process and provides reliable Pareto solutions, while BIM technology enhances the feasibility of construction schemes by simulating the construction process. This method offers architects the ability to quickly make optimal construction period/cost decisions based on previous data and visualizes the construction process with a dynamic schedule of the project.

The study by Juszczyk et al. [30] delves into the potential integration of artificial intelligence (AI) into the domain of cost management within the construction industry. Specifically, the research endeavors to develop a novel simulation technique employing a large ensemble of neural networks to accurately forecast construction costs for sports fields. This method distinguishes itself from the conventional neural network applications by utilizing multiple networks within the ensemble model. The investigation concentrates on the assessment of four predictors or models, uniquely tailored to incorporate sports field characteristics and construction costs. Among these, two ensembles, namely ENS 1 and GEN 2, incorporate networks with distinct architectural configurations and activation functions, whereas ENS 3 and GEN 4 are constructed using networks featuring comparable architectures and activation functions. Additionally, the study highlights the advantages of employing BIM models for expedient data extraction, which provides the necessary information for the cost analysis models.

2.4. Objectives and Paper Structure. Obviously, cost management throughout the project life cycle is imperative. Most existing studies have primarily concentrated on cost estimation, scheduling, and optimization in the early stages of projects [31–33] while giving less attention to cost control and decision-making during project execution. Owing to the inherent uncertainty surrounding costs throughout the engineering process, achieving cost control necessitates the probabilistic analysis of costs, employing probability distribution methods to depict the existing cost scenario. Simultaneously, to facilitate informed decision-making by the project managers, employing proper methods becomes essential to pinpoint the primary sources contributing to the cost issues.

Although current applications of 5D BIM can provide a cost schedule that can serve as a reference for decision-making, the inherent inaccuracy of quantity takeoff, and BOQs introduce inevitable uncertainty into the cost schedule. When actual costs deviate from the planned costs, it becomes important to determine whether this deviation is an abnormal risk or a normal fluctuation. Addressing these challenges requires the adoption of reliability analysis in the context of construction projects. Reliability analysis has proven effective in other engineering disciplines, such as structural and soil engineering, and recent research has also incorporated it into progress management. Hence, it is worth speculating whether reliability analysis can also be applied to cost management. Reliability analysis serves as a method employed to appraise the capacity of a system or component to execute its designated functions under specified conditions for a defined duration. This method encompasses a range of techniques to evaluate the reliability of diverse systems, including fault tree modeling, data-driven analysis, and hierarchical Bayesian network modeling. The primary objective is to ascertain the likelihood of failure and pinpoint potential areas necessitating enhancement in the system's reliability [34]. Through the integration of reliability analysis, we can evaluate and quantify uncertainties and risks linked to cost estimates, material utilization, and project scheduling. Specifically, when failure probability is quantified, surpassing a predetermined threshold signifies a heightened likelihood of an impending issue, mandating immediate remedial action.

Therefore, as the primary research objective of this study, a novel probabilistic approach is designed to help project managers in identifying potential sources of cost overruns, enabling them to take proactive measures. Then, to support this algorithm, a series of data collection workflows is developed to integrate information from BIM and onsite reports, thereby bridging the knowledge gap between project planning and execution within the domain of cost management. Additionally, a representative case study conducted in China is introduced, to preliminarily validate the practical viability of this algorithm.

The extensive review of existing literature has demonstrated that BIM could serve as an enabler for improved cost-management practices. Moreover, these pertinent works offer valuable perspectives and knowledge in this area. Nevertheless, it is imperative to underscore the scarcity of research dedicated to conducting a comprehensive assessment of the uncertainty linked to cost control measures, while uncertainty is the inherent nature of construction projects. This research gap is further accentuated by the need to establish methodologies that effectively align precise material measurement tools with cost management, mitigating uncertainty in the construction projects and accurately depicting the prevailing cost scenario. Such a research gap leads to flawed results and ultimately an inadequate evaluation of the project success. To address these challenges, there is a need to develop a more flexible probabilistic method that utilizes progress data in conjunction with a progress monitoring system. In this study, we attempt to develop a probabilistic approach for progress evaluation to quantify the risk of schedule delays. This algorithm effectively combines onsite management processes with reliability analysis techniques, to provide project managers more efficiency and comprehensibility. The four primary research objectives are enumerated as follows:

(1) Construct the correlation between cost and design models and progress without resorting to a detailed cost breakdown.
(2) Establish a numerical relationship between the expected current cost and the expected total cost with the current time.
(3) Quantify the risk of cost overruns and cost deviation and set warning thresholds.
(4) Determine the primary cause of cost exception.

The organization of the rest of this paper is summarized as follows: Section 3 provides the problem definition and then delves into the details of our mathematical model under necessary assumptions, emphasizing how we combine the theoretical data from BIM with the progress to estimate costs and make them probabilistic. This section also explains how we determine the primary causes when cost deviation occurs. Section 4 presents the implementation of the BIM-based project cost-management scheme. Section 5 demonstrates the application of our approach in four different cases based on a real-life construction project. Then, we discuss and analyze the results presented in Section 5; and further derive contributions and limitations of our method and present our conclusion in Section 6.

3. Methodology

3.1. Problem Definition. Risk can be described as the objective uncertainty and consequences resulting from unexpected occurrences. In our case, risk in construction projects is mainly manifested in total cost overruns and cost deviation, which can significantly impact the project's progress. Therefore, it is necessary to monitor the cost throughout the project life cycle, warn of possible risks and further locate the causes when risks may occur. Specifically, due to various uncertainties in the construction that we will explain below, problems can be expressed as Equations (1) and (2):

$$P(\mathrm{ETC}(t) \geq \mathrm{Budget}) \geq \alpha, \tag{1}$$

$$P\left(\frac{|\mathrm{SCC}(t)-\mathrm{ACC}(t)|}{\mathrm{SCC}(t)} \geq \delta\right) \geq \beta, \tag{2}$$

where $\mathrm{ETC}(t)$ represents expected total cost at the end of the project and $\mathrm{SCC}(t)$ and $\mathrm{ACC}(t)$ represent scheduled current cost and actual current cost at time t.

To express our belief that the discrepancy between the scheduled cost and the actual cost at time t within a specific range is acceptable, we have introduced a parameter δ and have adopted $P(\frac{|\mathrm{SCC}(t)-\mathrm{ACC}(t)|}{\mathrm{SCC}(t)} \geq \delta)$ as the check value, which indicates the probability of the relative error of the actual cost from the scheduled exceeding a specific range. Compared to directly calculating $P(\mathrm{SCC}(t) \geq \mathrm{ACC}(t))$, our method permits more precise control of the admissible error and warning threshold, which is more effective when we desire to control costs in different aspects. Moreover, α, β, and δ are all adjustable hyperparameters that control the sensitivity of the algorithm.

Therefore, the question is how to estimate $\mathrm{ETC}(t)$ and $\mathrm{SCC}(t)$; and calculate the probability density functions P $(\mathrm{ETC}(t))$ and $P(\frac{|\mathrm{SCC}(t)-\mathrm{ACC}(t)|}{\mathrm{SCC}(t)})$. In our method, we have introduced expected current cost denoted as $\mathrm{ECC}(t)$ to the calculation of $\mathrm{ETC}(t)$, which is also helpful for the cost-deviation analysis.

It should be evident that we can aggregate all the cost items at time t to obtain the total cost and compare it to the scheduled cost to determine the risks. However, in reality, during the project, it is often challenging to acquire all the accurate real-time data necessary to predict the cost at the end of the project and calculate the deviation. To address this issue, we propose an estimation and calculation method based on BIM to assist with cost management. In our model, project P is composed of a series of tasks P_i, and each P_i, consists of small cost items P_{ij}, where i and j are positive integers. Hence, P_{ij} can represent all cost items of the project. It should be noted that P_{ij} may correspond to the same type of cost item for different i and j, but this does not impact our mathematical model. Subsequently, $\mathrm{SCC}(t)$, $\mathrm{ECC}(t)$, and $\mathrm{ETC}(t)$ can be described by Equations (3)–(5):

$$\mathrm{SCC}(t) = \sum_i \sum_j \left(C_{ij} \times \lambda_{ij}(t)\right), \tag{3}$$

$$\mathrm{ECC}(t) = \sum_i \sum_j \left(C_{ij} \times \lambda'_{ij}(t)\right), \tag{4}$$

$$\mathrm{ETC}(t) = \mathrm{ACC}(t) + (\mathrm{ECC}(t_{\mathrm{end}}) - \mathrm{ECC}(t)), \tag{5}$$

where C_{ij} denotes the cost of P_{ij}, and t_{end} represents the end time of the project. $\lambda_{ij}(t)$ and $\lambda'_{ij}(t)$ signify the scheduled cost percentage and actual cost percentage of P_{ij} at time t. Assuming that all unfinished tasks will be completed as planned, $\mathrm{ECC}(t_{\mathrm{end}})-\mathrm{ECC}(t)$ signifies the estimated value of the latter cost required in Equation (5), so the sum of $\mathrm{ACC}(t)$ and ECC $(t_{\mathrm{end}})-\mathrm{ECC}(t)$ signifies $\mathrm{ETC}(t)$. Additionally, if the schedule is modified, the entire model must be updated to ensure the validity of the definition. Next, we consider how to estimate C_{ij}.

Assuming that all costs such as material costs, labor costs, and mechanical costs are integrated into unit prices p_{ij} for each cost item, indicating C_{ij} can be computed using Equation (6).

$$C_{ij} = q_{ij} \times p_{ij}, \tag{6}$$

where q_{ij} is the quantity of P_{ij}. Since p_{ij} can be provided by experts, C_{ij} can be estimated using Equation (6), and $\lambda_{ij}(t)$ can be computed using the schedule, then the question focuses on how to obtain the quantity of each P_{ij}. Naturally, we considered using BIM to calculate the quantity for each cost item; however, it is not reasonable to use theoretical quantity data from BIM directly due to manufacturing losses. For example, losses are caused by cutting original materials due to the need for different sizes of rebars in actual engineering. Additionally, cement always consumes more than expected due to processing technology and construction site conditions. Besides, due to progress advances or delays, the actual quantities will vary from the schedule, which also contains uncertainty. Furthermore, it is demanding to measure the detailed quantities consumed of each cost item at each time point; therefore, we need to estimate quantities with the assumption of their distribution. In our method, based on BIM data, we have manufacturing losses correction and progress exception correction to evaluate the actual quantities in progress of the project.

3.2. Quantity Correction. In this section, we seek to explain the process of revising theoretical and scheduled quantities, particularly in the context of the natural uncertainty inherent in construction projects, which primarily manifests as quantitative uncertainties in our approach. Given that the quantity derived from BIM does not always align with the actual consumption on site, it is necessary to execute a quantity correction process. Additionally, as the actual progress may deviate from the scheduled progress, the quantity also needs to be revised. To address these two sources of potential exceptions, we utilize distinct methods for their correction.

3.2.1. Manufacturing Losses Correction. Taking the losses of materials into account, the expected quantity for each cost item P_{ij} should be greater than its theoretical value, and it is intuitive to introduce the parameter k_{ij} to describe the ratio of the expected quantity to the theoretical value. Consider the fact that the types of materials and the processes and construction sites differ, the material loss rate is not uniquely determined, but rather a random variable with a certain degree of randomness. Under the assumption that k_{ij} follows a normal distribution with a mean of μ_{ij} and standard deviation σ_{ij}, the corrected scheduled quantity of P_{ij}, which we denote as $\widehat{q}_{ij}$, can be expressed as Equation (7):

$$\widehat{q}_{ij} = k_{ij} \times q_{ij}, k_{ij} \sim \mathcal{N}\left(\mu_{ij}, \sigma_{ij}^2\right). \tag{7}$$

It is worth noting that the parameters of k_{ij} can be initially estimated by experts and updated with data from actual engineering projects to obtain a better estimation performance. Through this approach, we achieve the correction for manufacturing losses.

3.2.2. Progress Exception Correction. Obviously, if the project's progress deviates from the schedule, the consumption of materials will also vary, which can lead to cost exceptions. Before comparing with the actual current cost, it is necessary to calculate the scheduled current cost, which requires calculating the scheduled quantity of each cost item P_{ij}.

Assuming that all cost items in P_i are carried out simultaneously and materials are consumed linearly, with start time st_{ij} and end time et_{ij} equal for cost items of the same task (i.e., $st_{ij} = st_i \,\&\, et_{ij} = et_i \,\&\, \lambda_{ij} = \lambda_i$), we can use the Equation (9) to obtain the scheduled quantity $\widehat{q}_{ij}^{s}(t)$ of cost item P_{ij} and calculate SCC(t). Additionally, Equation (8) indicates how to calculate the scheduled quantity percentage $\lambda_i(t)$ at time t, and actual progress can be considered the actual quantity percentage. While we desire to monitor the deviation between SCC(t) and ACC(t), the progress of each task can interfere with our assessment, for which reason, the quantities need to be revised based on the actual progress, which we refer to the expected quantities $\widehat{q}_{ij}^{e}(t)$ using Equation (10). After excluding progress exceptions, we obtain the expected quantities, which can assist in analyzing the sources of errors.

$$\lambda_i(t) = \begin{cases} 0, t < st_i \\ \dfrac{t - st_i}{et_i - st_i}, st_i \leq t \leq et_i, \\ 1, t > et_i \end{cases} \tag{8}$$

$$\widehat{q}\,_{ij}^{s} = \lambda_i(t) \times \widehat{q}_{ij}(t), \tag{9}$$

$$\widehat{q}\,_{ij}^{e} = \lambda_i'(t) \times \widehat{q}_{ij}(t). \tag{10}$$

3.3. Cost-Overruns Detection. In this section, we utilize the expected total cost calculated by our model and the budget to perform a cost-overruns analysis. In previous sections, we provided the expected total cost of the project at time t as Equation (5), from which we can see that to calculate ETC(t), it is necessary to calculate ECC(t). Noting that ACC(t), $\lambda_i'(t)$, and p_{ij} are constants at time t, while $\widehat{q}_{ij}$ is considered a random variable due to the uncertainty related to k_{ij}, we have explained that k_{ij} follows a normal distribution that can be described as Equation (7), which means that for each i, j, the distribution of C_{ij} could be expressed as Equation (11). We then obtain the distribution of the expected current cost at time t as Equation (12) in virtue of the additive nature of the normal distribution for independent random variables. Theoretically, we can calculate the distribution of expected total cost at time t using Equation (5) and its probability density function P(ETC(t)). Furthermore, we can calculate the probability of overruns using Equation (13) and provide a warning if Equation (1) is satisfied.

$$\begin{aligned} C_{ij}(t) = \lambda_i'(t) k_{ij} \widehat{q}_{ij}(t) p_{ij}, k_{ij} \sim \mathcal{N}\left(\mu_{ij}, \sigma_{ij}^2\right) \\ \sim \mathcal{N}\left(\theta_{ij}(t)\mu_{ij}, \left(\theta_{ij}(t)\sigma_{ij}\right)^2\right), \theta_{ij}(t) = \lambda_i'(t)\widehat{q}_{ij}(t)p_{ij}, \end{aligned} \tag{11}$$

$$\mathrm{ECC}(t) \sim \mathcal{N}\left(\sum_i \sum_j \theta_{ij}(t)\mu_{ij}, \sum_i \sum_j \left(\theta_{ij}(t)\sigma_{ij}\right)^2\right), \tag{12}$$

$$P(\mathrm{ETC}(t) \geq \mathrm{Budget}) = \int_{\mathrm{Budget}}^{\infty} P(\mathrm{ETC}(t))\mathrm{dETC}(t). \tag{13}$$

In practical applications, we can calculate the reliability constraint expressed as Equations (14) and (15), where Φ represents the cumulative distribution function of the standard normal distribution, $\mu_{\mathrm{ETC}(t)}$ and $\sigma_{\mathrm{ETC}(t)}$ signify the mean and the standard deviation of ETC(t), respectively. If $\text{Pb} \geq \text{Th}$, it indicates that Equation (1) is valid.

$$\text{Th} = \alpha, \tag{14}$$

$$\text{Pb} = \Phi\left(\frac{\text{Budget} - \mu_{\text{ETC}(t)}}{\sigma_{\text{ETC}(t)}}\right). \tag{15}$$

3.4. Cost-Deviation Detection. Combined with Equation (12) mentioned in the previous section, we can apply it to cost deviation detection, which is the main focus of this section. Since, we already have the distribution of SCC(t) and the actual current cost ACC(t) at time t, calculating the probability density function of $\frac{|\text{SCC}(t)-\text{ACC}(t)|}{\text{SCC}(t)}$ is a natural idea. Considering that there is likely an error between the scheduled current cost and the actual current cost, we believe their error is reasonable within a certain range. Therefore, we use Equation (16) to calculate $P(\frac{|\text{SCC}(t)-\text{ACC}(t)|}{\text{SCC}(t)} \geq \delta)$, and if it is greater than the threshold (i.e., Equation (2) is satisfied), the current cost is considered unreasonable. In this situation, we need to warn of the risks of cost deviation.

$$P\left(\frac{|\text{SCC}(t) - \text{ACC}(t)|}{\text{SCC}(t)} \geq \delta\right) = 1 - \int_{\text{ACC}(t)/1-\delta}^{\text{ACC}(t)/1+\delta} P(\text{SCC}(t))\text{dSCC}(t), \tag{16}$$

where P(SCC(t)) represents the probability density function of SCC(t). Additionally, as in the previous section, we can use Φ for calculations, which is shown in Equations (17) and (18), where $\mu_{\text{SCC}(t)}$ and $\sigma_{\text{SCC}(t)}$ signify the mean and the standard deviation of SCC(t). If $1-\text{Pb}' \geq \text{Th}'$, it indicates that Equation (2) is valid.

$$\text{Th}' = \beta, \tag{17}$$

$$\text{Pb}' = \Phi\left(\frac{\frac{\text{ACC}(t)}{1-\delta} - \mu_{\text{SCC}(t)}}{\sigma_{\text{SCC}(t)}}\right) - \Phi\left(\frac{\frac{\text{ACC}(t)}{1+\delta} - \mu_{\text{SCC}(t)}}{\sigma_{\text{SCC}(t)}}\right). \tag{18}$$

3.5. Risk Reasoning. The goal of our work is not only to identify risks but also to locate their source, which requires additional analysis when warnings are issued. In our model, cost deviation can only stem from quantity and progress, meaning that at least one is flawed. Given the correlation between the two, we need to separate their impact. If a risk occurs, our method involves correcting the expected current quantity based on the relationship between actual and scheduled progress, which we have detailed in the previous sections. Once corrected quantities are obtained, we calculate the corrected expected current cost $\text{ECC}'(t)$ the same way as ECC(t), which we have used in the cost-overruns detection. Thus, we conduct risk reasoning in two steps. First, we calculate $P(\frac{|\text{ECC}'(t)-\text{ACC}(t)|}{\text{ECC}'(t)} \geq \delta)$. If $P(\frac{|\text{ECC}'(t)-\text{ACC}(t)|}{\text{ECC}'(t)} \geq \delta) \leq \beta$, it indicates that the cost calculated based on the theoretical quantity corresponding to the current progress is within a acceptable range, so the main reason for cost deviation is the progress. Conversely, if $P(\frac{|\text{ECC}'(t)-\text{ACC}(t)|}{\text{ECC}'(t)} \geq \delta) > \beta$, it indicates that there is a problem with the quantity in addition to progress because there is still a risk of cost deviation even with normal progress. Then, we can further analyze the current cost situation if the deviation is mainly caused by quantity. If $\mu_{\text{ECC}'(t)} - \mu_{\text{ACC}(t)} \geq 0$, then it can be considered that there is a dangerous possibility of cutting corners because the material consumption is relatively low under the expected progress, which is very unreasonable and can be considered as a risk. Also, if $\mu_{\text{ECC}'(t)} - \mu_{\text{ACC}(t)} < 0$, then there may be some degree of material waste. In this way, we complete the reasoning of risks and cost monitoring by judging the difference between $\text{ECC}'(t)$ and ACC(t) and provide further possible scenarios if there are problems with the quantity. Additionally, since we only monitor cost, when there is a deviation in both schedule and quantity under certain conditions, the cost may behave as expected while actual construction has deviated from the plan. Therefore, we also need to combine schedule progress detection or other methods for the cost management.

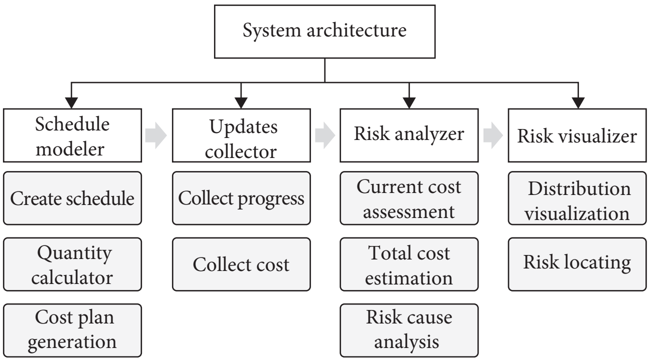

Figure 1: Basic framework of project cost-management scheme based on our algorithm.

4. Implementation of BIM-Based Project Cost-Management System

4.1. System Architecture. In this section, we present the implementation of the project cost-management scheme. Our novel approach uses a web-based platform that facilitates project scheduling, collects schedule and cost data, assesses cost-overruns risks, and visualizes risks. Figure 1 depicts the architecture of the proposed system, which includes the following key components.

(1) The Project Scheduling Module: This module is responsible for creating and managing project plans, including establishing the work breakdown structure (WBS), specifying task lists, setting up schedules, and developing project budgets. This information would

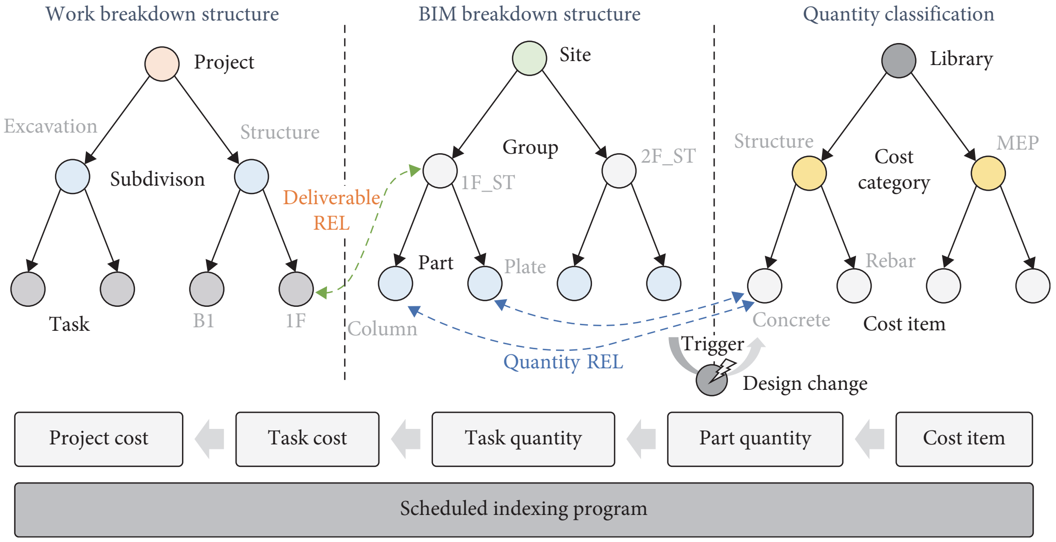

FIGURE 2: Illustration of integration of BIM quantities, WBS, and project cost.

generate a cost plan that serves as the baseline for project execution.

(2) Data Collection Module: This module is used to collect the progress and cost data from the project personnel. It provides a user-friendly interface that allows users to update project schedules and cost information easily. This data can then be used for subsequent analysis and visualization purposes.

(3) Risk Assessment Module: This module automatically assesses cost overruns risks based on the collected data. Our proposed statistical algorithm is used in this module to analysis the data and identify potential risks. It will generate quantitative risk assessment by taking into account various factors, including the current status of project execution, project quantities, and cost plan.

(4) Visualization Module: This module is designed to provide a visual representation of the risk assessment results. It utilizes charts, dashboards, and other visualization tools to enable users to visualize the status of a project overruns risk. These visualization results not only assist the project team in obtaining a comprehensive understanding of the current status of the project but also enable them to make informed decisions and necessary adjustments based on the assessment.

4.2. Data Integration. Quantity estimation is the basis of cost management and usually requires experienced project managers to conduct detailed assessments and measurements to estimate task duration based on drawings. However, this process can be very time-consuming and difficult, especially when the design changes and requires a complete recalculation of the relevant quantities. Therefore, developing an algorithm that automatically generates task duration estimates is key to increasing productivity and simplifying the estimation process.

In our design, we adopt the entity–relationship (E–R) model to model components and cost items connected by specific relationships. To implement this model, we build predefined component templates. When we instantiate a template or modify instance parameters, the relevant parts recalculate the quantities and update the connections. The scheduler then indexes these connections and automatically aggregates the quantities based on the corresponding cost items to generate a cost item list. The calculated quantity is multiplied by the price and then summed to obtain the total cost of the project or task. This mechanism ensures that we always have the latest quantities and planned costs. This process is shown in Figure 2.

4.3. Dynamic Risk Analysis. During the execution of a project, it is essential to record regular updates on progress and cost. Recorded progress and cost information not only enable project managers to keep track of the project's status but also allow them to make informed decisions about deviation correction, resource allocation, and future planning. As shown in Figure 3, in our design, progress reporting includes three elements: “scope,” ”progress,” and ”progress acceptance”. “Scope” specifies the scope of the reported work within the WBS. ”Progress” refers to the level of workload completion at any given time. Each submission generates an acceptance process for supervisor acceptance, and only the reported and accepted workload is recorded. Additionally, up-to-date total cost is regularly collected for comparison with the planned cost, providing data for the following assessment process.

After that, the planned current cost is estimated by collected progress data using the algorithm mentioned above, and compared to the real current cost, which is collected regularly from a project personnel. Our algorithm will give a probable range of current cost according to the cost plan. If the actual cost is out of this range, then an alert will be sent to the project managers. Besides, our algorithm of cost-overruns detection will also estimate the distribution of total cost given existing cost data. If the cost-overruns probability

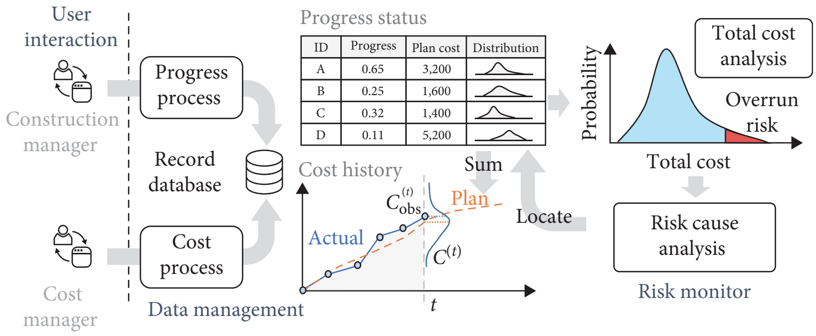

FIGURE 3: Illustration of data collection and risk analysis. In this workflow, progress and cost data are collected and applied to our algorithm, which identifies the potential risk of cost overruns and cost deviation. By integrating cost history and algorithm prediction, advice can be provided to managers.

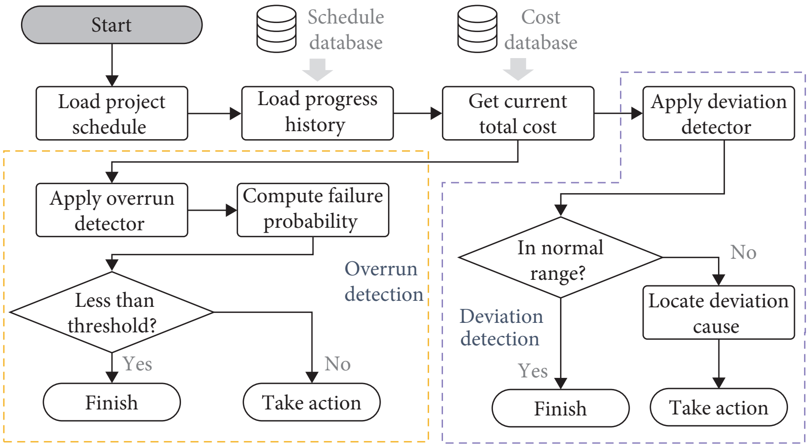

FIGURE 4: Schematic representation of risk analysis. In this diagram, our approach executes cost-overruns detection procedures to identify potential cost overruns based on schedule, progress, and current cost. Cost-deviation detection is implemented to estimate the occurrence of cost variances, and then risk reasoning techniques are applied to determine the primary causal factors if there is an exception.

exceeds the predefined threshold, an alert from our system will remind project managers to take actions and help them to identify the potential cause by deviation detection and risk locating. This process is shown in Figure 4. And the flowchart of the two processes are shown in Figure 5.

5. Experiment and Results

To verify the efficiency and reliability of the BIM-based cost-management method, we employed data from a medical building construction project in Wuhan, Hubei Province. We extracted the construction schedule and theoretical material usage for each cost item from the BIM platform, and then tested the algorithm using hypothetical data. The BIM-derived scheduled data are displayed in Figures 6 and 7 and Table 1.

In this paper, we established the parameters in Tables 2 and 3. Subsequently, we conducted simulation experiments with various hypothetical current progresses and current costs. We used four different datasets to validate the approach which we have developed, and the results were compiled in Table 4 and Figures 8–11. It should be noted that these datasets come from different stages of the same project, and their Gantt charts are shown in Figures 8–11.

Next, to investigate the influence of δ in the algorithm, we adjust δ and conduct experiments based on Case 3. The parameters and corresponding results are shown in Table 5.

6. Discussion and Conclusion

6.1. Discussion. From the results presented in the previous section, we can discuss the following points.

In the individual cases, Case 2 exhibits cost deviation mainly due to excessive consumption of materials; Case 3 indicates cost deviation mainly caused by progress exceptions; Case 4 indicates there is a 39.98% chance of cost overruns and a 21.83% probability of cost deviation, signifying a definite risk of cost overruns. Using our method, there is a 21.09% probability of cost overruns and a 99.99% probability of cost deviation in Case 2, and there is still a 99.99% probability of deviation after excluding progress factors, leading us to determine that the cost deviation is mainly due to excessive consumption of materials. In Case 3, our algorithm gives a 2.29% chance of cost overruns and an 83.86% probability of the cost deviation. After excluding schedule factors, the probability of deviation jumps to 24.02%, signifying that the cost deviation is mainly caused by progress exceptions.

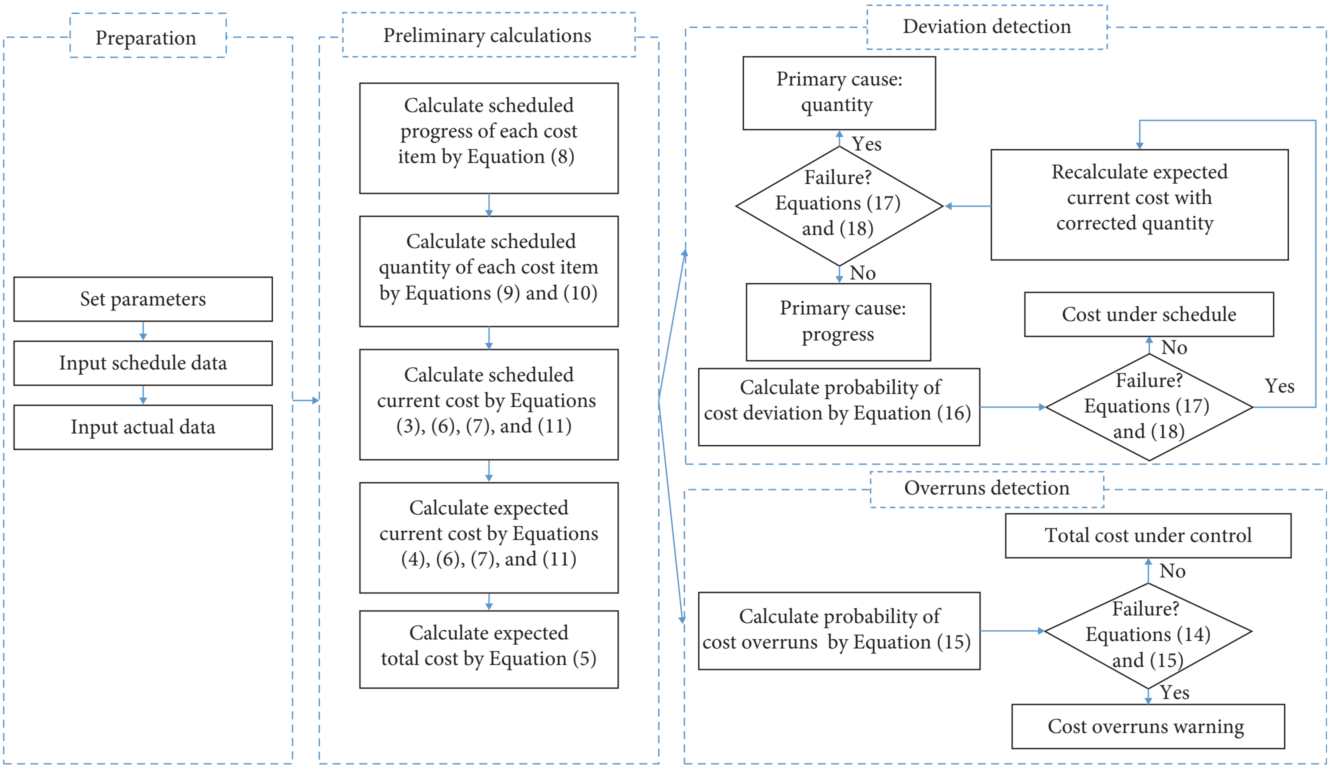

FIGURE 5: Flowchart of overruns detection and deviation detection. From this flowchart, in the preparation phase, we set parameters like k_{ij}, p_{ij} and input necessary schedule data as well as actual cost and progress. Then in the preliminary calculations phase, we perform some precalculations required for the subsequent judgment algorithm. Next, we can conduct overruns detection and deviation detection. The formulas involved in the steps are all marked in the figure.

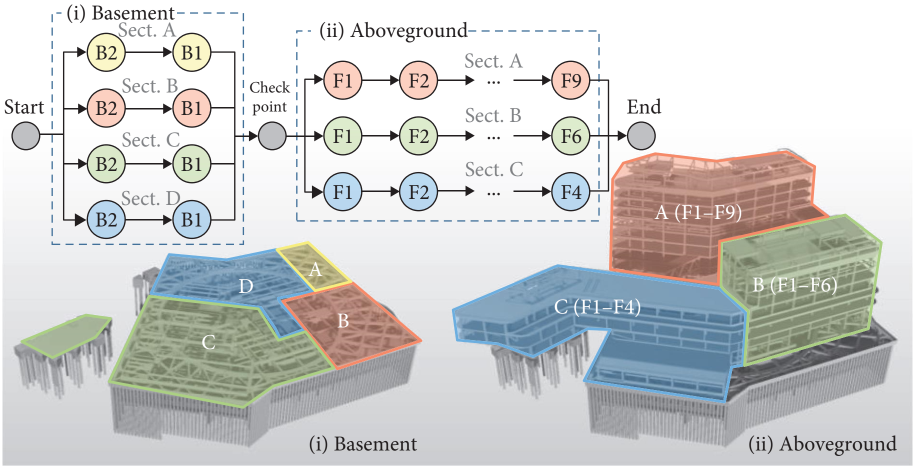

FIGURE 6: Construction schedule.

Next, in multiple cases, Case 1 and Case 4 demonstrate that our algorithm can identify the risk of cost overruns without requiring detailed cost data during construction. Additionally, from Case 1 and Case 2 to Case 3, our algorithm is capable of detecting the risk of cost deviation. The results of Case 2 and Case 3 suggest that the algorithm can pinpoint the primary cause of current cost deviation based on different situations when errors occur. The results of Case 2 and Case 3 to Case 4 indicate that our algorithm can simultaneously detect cost overruns and cost deviation. Through Case 1 to Case 4, we have validated the effectiveness of our algorithm in cost management and its ability to provide valuable insights for reference throughout different stages of the project cycle.

Moreover, based on the above cases, even in the absence of cost-overruns warnings, it does not imply that cost is proceeding according to plan (Case 2 and Case 3), indicating that reliance on the risk of cost overruns alone cannot

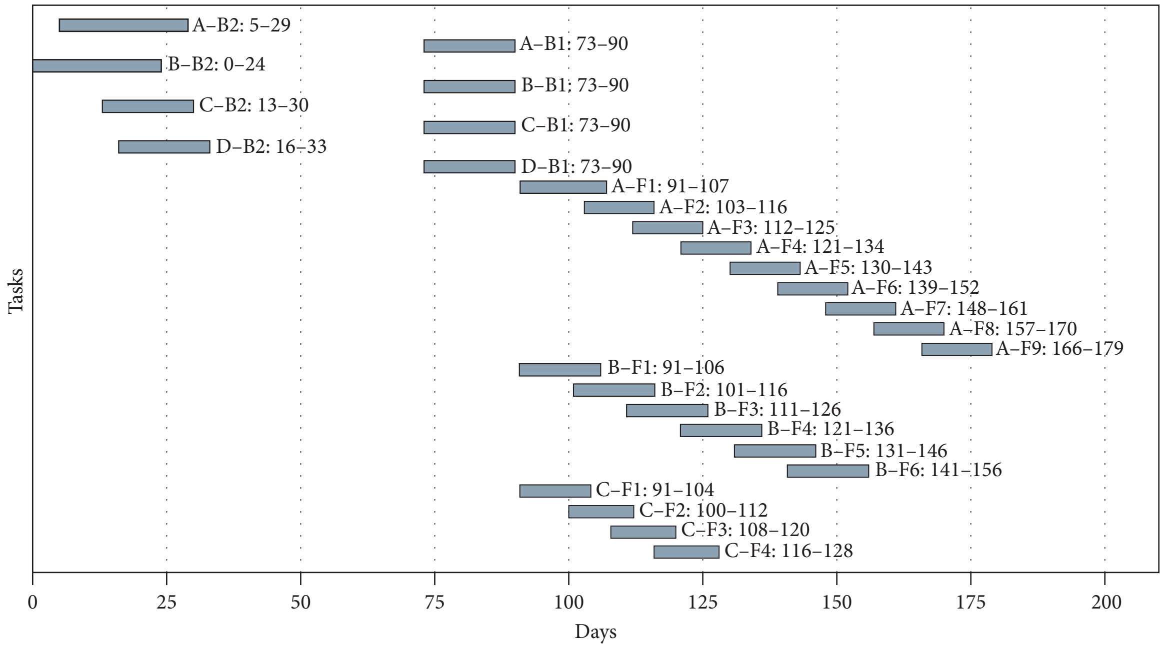

Figure 7: Scheduled progress.

Table 1: Scheduled material.

Task name	Concrete (m^3)	Steel (m^3)	Rebar (m^3)
Section A B2	383.364	0	4.600368
Section A B1	420.701	0	5.048412
Section B B2	855.273	0	10.263276
Section B B1	822.997	0	9.875964
Section C B2	1,091.306	0	13.095672
Section C B1	1,554.421	0	18.653052
Section D B2	1,032.931	0	12.395172
Section D B1	1,235.256	0	14.823072
Section A F1	41.082	215.185	0.246492
Section A F2	0	204.203	0
Section A F3	2.296	174.329	0.013776
Section A F4	16.515	165.99	0.09909
Section A F5	6.318	161.718	0.037908
Section A F6	11.399	162.345	0.068394
Section A F7	6.351	158.392	0.038106
Section A F8	6.003	159.327	0.036018
Section A F9	81.103	163.361	0.486618
Section B F1	14.803	263.164	0.088818
Section B F2	0	299.953	0
Section B F3	13.086	263.409	0.078516
Section B F4	86.639	191.355	0.519834
Section B F5	4.563	183.254	0.027378
Section B F6	71.109	189.051	0.426654
Section C F1	50.791	214.725	0.304746
Section C F2	0	223.335	0
Section C F3	21.313	223.991	0.127878
Section C F4	25.23	228.924	0.15138

Table 2: Algorithm parameter settings in case study.

Parameters in algorithm		
Threshold	α	0.32
	β	0.32
Accepted range	δ	0.5
Budget	Budget	200

The unit of budget is million yuan (CNY).

Table 3: Material parameter settings in case study.

Parameters in material			
Material type	Concrete	Steel	Rebar
μ	1.2	1.2	1.2
σ	0.5	0.5	0.5
Price	450	27,846	36,895

The unit of price is yuan (CNY).

determine whether the current cost is being implemented as planned, which is why we introduce cost-deviation detection into our algorithm. Another noteworthy aspect is that if the consumed quantity is less than expected and the progress is faster than expected or vice versa, cost-overruns detection may fail (Case 2 and Case 3), but deviation detection will still identify the current problem and further classify it as either cutting corners or excessive material consumption by the mean value of ECC(t). Meanwhile, we can also find that even if the cost follows the plan, there may still be cost overruns (Case 4), which could be explained by a relatively

Table 4: Hypothetical data and results.

	Item	Case 1	Case 2	Case 3	Case 4
Time and cost	Days	40	80	120	160
	Current cost	4	25	50	150
Progress of each task	Section A B2	1.0	1.0	1.0	1.0
	Section A B1	0.15	0.76	1.0	1.0
	Section B B2	1.0	1.0	1.0	1.0
	Section B B1	0.15	0.49	1.0	1.0
	Section C B2	1.0	1.0	1.0	1.0
	Section C B1	0.09	0.32	1.0	1.0
	Section D B2	1.0	1.0	1.0	1.0
	Section D B1	0.1	0.59	1.0	1.0
	Section A F1	0	0	1.0	1.0
	Section A F2	0	0	1.0	1.0
	Section A F3	0	0	1.0	1.0
	Section A F4	0	0	0	1.0
	Section A F5	0	0	0	0
	Section A F6	0	0	0	0
	Section A F7	0	0	0	0
	Section A F8	0	0	0	0
	Section A F9	0	0	0	0
	Section B F1	0	0	1.0	1.0
	Section B F2	0	0	1.0	1.0
	Section B F3	0	0	0.5	1.0
	Section B F4	0	0	0	0.72
	Section B F5	0	0	0	0
	Section B F6	0	0	0	0
	Section C F1	0	0	1.0	1.0
	Section C F2	0	0	1.0	1.0
	Section C F3	0	0	0.31	1.0
	Section C F4	0	0	0	0.49
Results	Overruns deviation reasoning	False (12.63%) False (26.82%) —	False (21.09%) True (99.99%) Quantity (99.99%)	False (2.29%) True (83.86%) Progress (24.02%)	True (39.98%) False (21.83%) —

Next, to investigate the influence of δ in the algorithm, we adjust δ and conduct experiments based on Case 3. The parameters and corresponding results are shown in Table 5.

insufficient budget in the project or perhaps by overly strict parameter settings in our algorithm, resulting in excessive risk assessment of cost overruns. Evidently, α and β are only thresholds controlling whether a warning is given and do not affect the calculation process of the algorithm. In contrast, δ directly impacts the calculation of Equation (16), meaning it has a different effect from α and β. It can be concluded that the smaller values of α or β result in a higher sensitivity of the algorithm to anomaly detection. Then, we discuss the role of δ in the deviation detection.

Given that δ only participated in the cost-deviation detection, it can be observed from Table 4 that the cost-overruns detection remained unchanged in all three cases, but there were significant differences in the deviation detection. The results suggest that δ does not only affect the calculation of risk probability but also impacts the judgment of deviation reasoning. In other words, in our algorithm, δ represents the acceptable range of cost deviation, meaning that a larger δ indicates allowing for a larger deviation range, and a smaller δ increases the likelihood of the algorithm judging the deviation as a quantity problem due to the larger value of Equation (16) after excluding progress exceptions. Another notable aspect is that the δ should not be too small since this can make the algorithm extremely prone to giving deviation warnings. Consider the cases where $\delta \rightarrow 0$ ort $\delta \rightarrow 1$, the algorithm would almost always or never give an exception, which renders the algorithm meaningless. Therefore, parameter selection is also an essential component of the algorithm.

By treating the quantity of material consumption as a random variable, we have determined the current expected cost and the expected total cost and evaluated the risk of cost overruns and cost deviation based on their probability density function and the actual current cost. In our method, risks were quantitatively evaluated without employing detailed

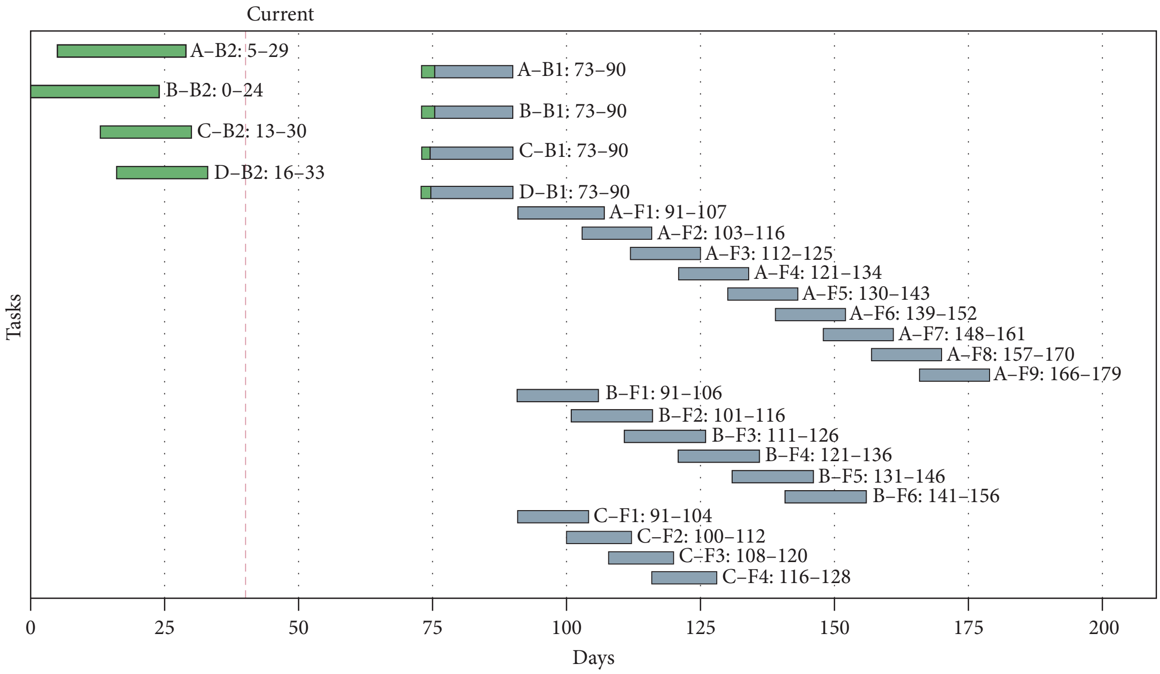

Figure 8: Current progress of Case 1.

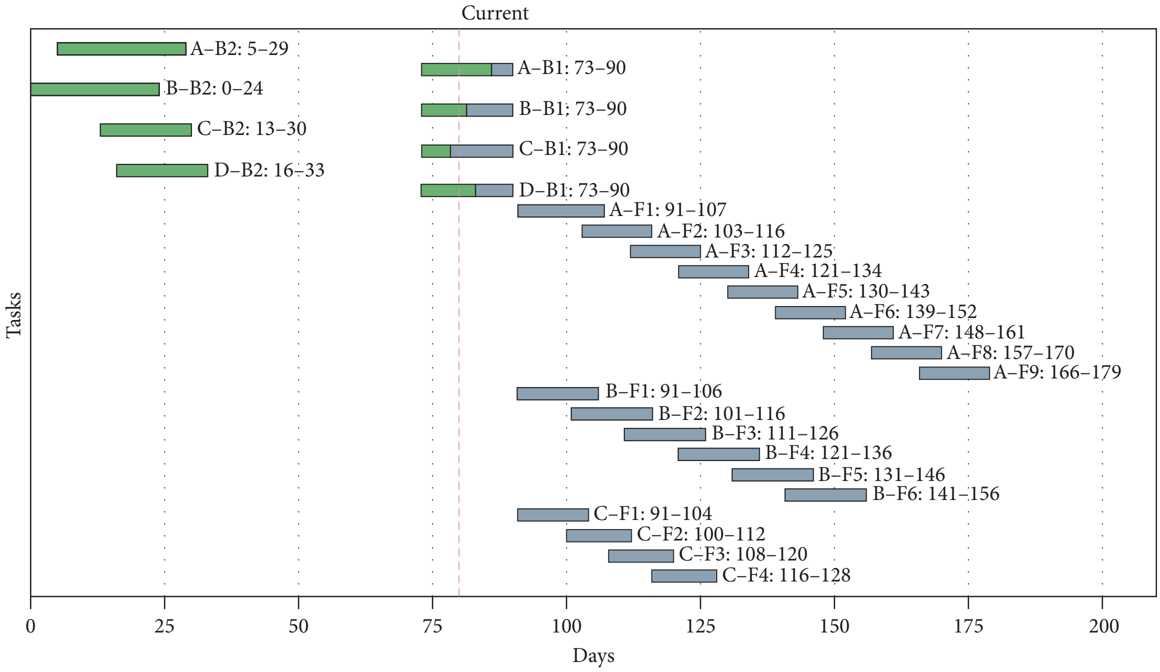

Figure 9: Current progress of Case 2.

cost of each cost item. Through the probabilistic approach, we can achieve scientific and quantitative cost management.

6.2. Conclusion. Our case study has shown that the proposed system and algorithm are effective and practical in the real-world applications. Through the case study presented above, we have established that our approach can accurately detect cost overruns and cost-deviation risks and provide primary causes. Compared to the traditional method of simply summing all cost details and making human judgments, our approach does not require the input of managers' experience, and our algorithm is also more scientific and intuitive. Additionally,

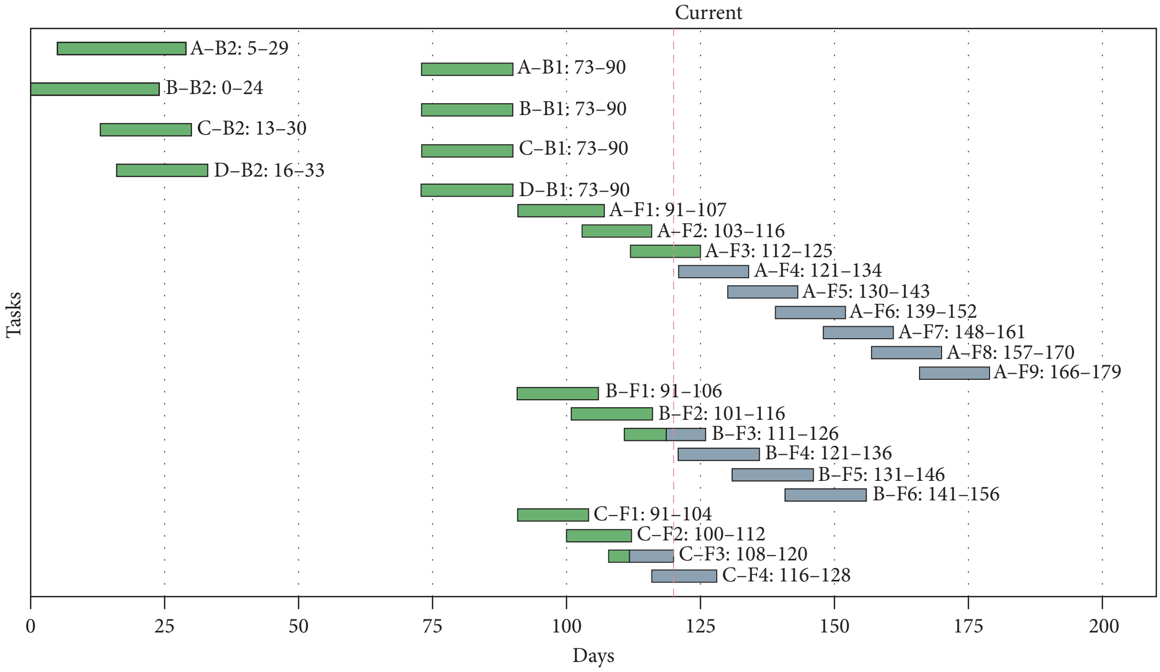

Figure 10: Current progress of Case 3.

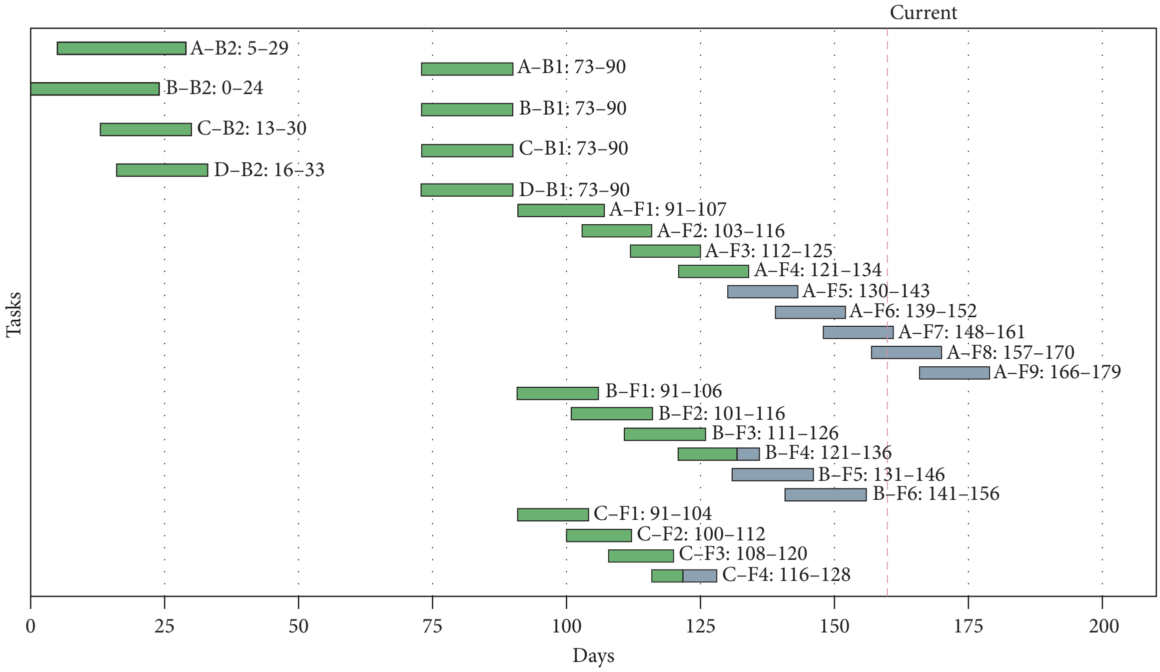

Figure 11: Current progress of Case 4.

Table 5: Results of different δ on Case 3.

Parameters	Overruns (%)	Deviation (%)	Deviation* (%)	Reasoning
Case 3.1: $\alpha = 0.32$, $\beta = 0.32$, $\delta = 0.5$	2.29	83.86	24.02	Progress
Case 3.2: $\alpha = 0.32$, $\beta = 0.32$, $\delta = 0.2$	2.29	96.49	75.36	Quantity
Case 3.3: $\alpha = 0.32$, $\beta = 0.32$, $\delta = 0.8$	2.29	10.31	—	—

Deviation* refers to the deviation probability without progress exceptions.

different parameters in the algorithm can also significantly affect the results, and managers can adjust them based on their sensitivity requirements for the project cost management.

Our main contribution is listed below:

(1) We transformed the consumption of various materials of each cost item into random variables, computed expected current cost and expected total cost to achieve cost estimation, and laid the foundation for subsequent analysis.

(2) We introduced the reliability analysis method into the field of cost management and combined it with cost distribution to provide the probability of different risks, achieving a quantitative analysis of the risk probability.

(3) Our approach integrated BIM theoretical data and on-site construction progress to achieve full process monitoring of construction cost management, providing project managers with continuous and reliable cost-risk assessment.

(4) Our research introduced a novel approach for quantification of cost overruns and cost deviation risks and determination of the primary causes, and some parameters in the method can be continuously updated in practice, making the algorithm more accurate in predicting construction project costs.

However, there are still some limitations of our method:

(1) Our research is based on several assumptions that may not entirely align with reality and could be improved. For instance, considering that k may not strictly follow a normal distribution, the algorithm may also have a certain level of deviation. Additionally, the consumption of various materials within a cost item may not occur simultaneously or linearly, which can also influence our approach especially in identifying the origin of risk. Although this does not impact the effectiveness of our algorithm, accounting for these aspects could make the algorithm more accurate and robust.

(2) An additional area for improvement is the lack of consideration for the temporal relationship in our method, which is because our algorithm does not analyze the relationship between the previous time and the current time. The timing relationship is another direction to improve the accuracy of cost-management algorithms. For example, if there is a cost-overruns warning at the current time when the previous was none, it could indicate that the exception was caused by the cost items during this period and thus more accurately locate any abnormalities.

(3) Our cost-overruns detection algorithm may theoretically fail in specific situations. For instance, when material consumption is significantly higher than expected while progress is delayed, the expected total cost may appear normal, causing our algorithm to potentially misjudge such exceptions. This probability is why our algorithm needs to be combined with progress or cost-deviation detection to eliminate such failures.

Cost management is a crucial component of construction project management, and it is also complex due to the difficulty of consistently obtaining accurate costs for each cost item throughout the entire project life cycle. To address, the challenge of whether there are risks and the probability of risks in cost management, we propose a novel algorithm to quantify the risk of cost overruns and cost deviation and identify the primary causes of exception. The results of our research show that our approach can effectively identify cost-related risks and determine their possible impact on a construction project. The main conclusions can be drawn as follows:

(1) Our study presents a novel probabilistic approach for quantification of cost-overruns risk and determination of the primary causes. We use the method of probabilistic material consumption for each cost item to calculate the current cost distribution and further estimate the expected total cost. Then, based on the probability distribution, combined with reliability analysis methods, obtain probability indicators for risk, which serve as the basis for our risk warning. If any abnormalities occur, the current scheduled cost will be revised based on the progress and compared with the actual cost again to locate the cause of the abnormality. Our case study demonstrated the efficiency and reliability of this method and discussed the influences of parameter settings.

(2) In our study, we propose a novel approach for estimating cost distribution, which enables managers to quickly and intuitively grasp the current project cost situation. The algorithm can serve as an effective reference for the project managers to make decisions, significantly reducing the experience requirements of the project managers. Additionally, the algorithm can adjust parameters according to actual needs and continuously update in practical use to obtain more accurate prediction results.

(3) We introduce a novel cost-management system that applies a probabilistic approach for the detection of cost exceptions. The proposed system combines BIM with probability theory and reliability analysis to quantitatively assess the risks of cost overruns and cost deviation. The system also utilizes BIM information and computational capabilities to provide accurate material data for each cost item, enhancing cost-estimation accuracy. BIM also plays a crucial role in visualizing the analysis results, enhancing comprehension and perception. The effectiveness and intuitiveness of the proposed system have been validated in our practical experiments.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This research was funded by the Major Program (JD) of Hubei Province (2023BAA007).

References

[1] I. A. Rahman, A. Hameed Mem, and A. T. Abd. Karim, “Significant factors causing cost overruns in large construction projects in Malaysia,” *Journal of Applied Sciences*, vol. 13, no. 2, pp. 286–293, 2013.

[2] Y. M. Cheng, “An exploration into cost-influencing factors on construction projects,” *International Journal of Project Management*, vol. 32, no. 5, pp. 850–860, 2014.

[3] H. Doloi, “Cost overruns and failure in project management: understanding the roles of key stakeholders in construction projects,” *Journal of Construction Engineering and Management*, vol. 139, no. 3, pp. 267–279, 2013.

[4] H. Luyue, L. Chang, R. Zhaojun, Z. Xiuyan, and Y. Huiqin, “Research on project cost management under the mode of bill of quantities valuation,” *International Journal of Frontiers in Engineering Technology*, vol. 4, no. 2, pp. 63–69, 2022.

[5] L. Liao, *Research on the application of BIM technology in the cost management of construction projects[C]//IOP Conference Series: Earth and Environmental Science*, vol. 783, p. 012098, IOP Publishing, 2021.

[6] J. Yang, *Application of BIM Technology in Construction Cost Management of Building Engineering[C]//Journal of Physics*, vol. 2037 of Conference Series, p. 012046, IOP Publishing, 2021.

[7] M. Parsamehr, U. S. Perera, T. C. Dodanwala, P. Perera, and R. Ruparathna, “A review of construction management challenges and BIM-based solutions: perspectives from the schedule, cost, quality, and safety management,” *Asian Journal of Civil Engineering*, vol. 24, no. 1, pp. 353–389, 2023.

[8] D. Mitchell, “5D BIM: Creating cost certainty and better buildings[C]//2012 RICS Cobra Conference,” 2012.

[9] A. Jrade and S. Alkass, “An integrated system for conceptual cost estimating of building projects,” *Cost Engineering*, vol. 44, no. 10, p. 28, 2002.

[10] D. Pontan, D. S K, A. M, A. T. P, D. M. B, and F. W, “Comparative study of bill of quantity planning and actual work mechanical, electrical and plumbing construction of hospital buildings,” *International Journal of Social Service and Research*, vol. 3, no. 8, pp. 1869–1872, 2023.

[11] O. Stopka, M. Stopková, I. Rybicka, P. Gross, and K. Jeřábek, “Use of activity-based costing approach for cost management in a railway transport enterprise,” in *Scientific Journal of*, Silesian University of Technology. Series Transport, 2021.

[12] D. David, D. Pordea, and L. Păiu an, “A study concerning the application of the activity-based costing method for entities operating in the building sector,” 2020.

[13] M. Proaño-Narváez, C. Flores-Vázquez, P. Vásquez Quiroz, and M. Avila-Calle, “Earned value method (EVM) for construction projects: current application and future projections,” *Buildings*, vol. 12, no. 3, p. 301, 2022.

[14] W. Xu, “Application of Earned Value Method in Project Cost Management and Schedule Management,” in *Proceedings of Business and Economic Studies*, 2021.

[15] C. Qing, “Research on second-level earned value method for improve evaluation of performance of engineering project,” 2006.

[16] C. M. Eastman, *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors[M]*, John Wiley & Sons, 2011.

[17] S. O. Babatunde, S. Perera, D. Ekundayo, and T. E. Adeleye, “An investigation into BIM-based detailed cost estimating and drivers to the adoption of BIM in quantity surveying practices,” *Journal of Financial Management of Property and Construction*, vol. 25, no. 1, pp. 61–81, 2019.

[18] M. Lawrence, R. Pottinger, S. Staub-French, and M. P. Nepal, “Creating flexible mappings between building information models and cost information,” *Automation in Construction*, vol. 45, pp. 107–118, 2014.

[19] F. H. Abanda, B. Kamsu-Foguem, and J. H. M. Tah, “BIM—new rules of measurement ontology for construction cost estimation,” *Engineering Science and Technology, an International Journal*, vol. 20, no. 2, pp. 443–459, 2017.

[20] D. Bryde, M. Broquetas, and J. M. Volm, “The project benefits of building information modelling (BIM),” *International Journal of Project Management*, vol. 31, no. 7, pp. 971–980, 2013.

[21] D. Kehily and J. Underwood, “Embedding life cycle costing in 5D BIM,” 2017.

[22] P. Smith, “Project cost management with 5D BIM,” *Procedia–Social and Behavioral Sciences*, vol. 226, pp. 193–200, 2016.

[23] McGraw Hill Construction, “The Business Value of BIM for Owners,” McGraw Hill Construction, New York, 2012.

[24] K.-C. Wang, W.-C. Wang, H.-H. Wang, P.-Y. Hsu, W.-H. Wu, and C.-J. Kung, “Applying building information modeling to integrate schedule and cost for establishing construction progress curves,” *Automation in Construction*, vol. 72, pp. 397–410, 2016.

[25] I. Alrashed and K. Kantamaneni, “A 5D building information model (BIM) for potential cost-benefit housing: a case of kingdom of Saudi Arabia (KSA),” *Infrastructures*, vol. 3, no. 2, p. 13, 2018.

[26] M.-A. Vigneault, C. Boton, H.-Y. Chong, and B. Cooper-Cooke, “An innovative framework of 5D BIM solutions for construction cost management: a systematic review,” *Archives of Computational Methods in Engineering*, vol. 27, no. 4, pp. 1013–1030, 2020.

[27] A. Baldrich Aragó, J. Roig Hernando, F. J. Llovera Saez, and J. Coll Bertran, “Quantity surveying and BIM 5D. Its implementation and analysis based on a case study approach in Spain,” *Journal of Building Engineering*, vol. 44, p. 103234, 2021.

[28] A. Amin Ranjbar, R. Ansari, R. Taherkhani, and M. R. Hosseini, “Developing a novel cash flow risk analysis framework for construction projects based on 5D BIM,” *Journal of Building Engineering*, vol. 44, p. 103341, 2021.

[29] W. He, Y. Shi, and D. Kong, “Construction of a 5D duration and cost optimisation model based on genetic algorithm and BIM,” *Journal of Engineering, Design and Technology*, vol. 17, no. 5, pp. 929–942, 2019.

[30] M. Juszczyk, K. Zima, and W. Lelek, “Forecasting of sports fields construction costs aided by ensembles of neural networks,” *Journal of Civil Engineering and Management*, vol. 25, no. 7, pp. 715–729, 2019.

[31] S. Kim and J. H. Shim, “Combining case-based reasoning with genetic algorithm optimization for preliminary cost estimation in construction industry,” *Canadian Journal of Civil Engineering*, vol. 41, no. 1, pp. 65–73, 2014.

[32] G. A. Barraza and R. A. Bueno, “Probabilistic control of project performance using control limit curves,” *Journal of*

Construction Engineering and Management, vol. 133, no. 12, pp. 957–965, 2007.

[33] G. A. Barraza, W. E. Back, and F. Mata, “Probabilistic monitoring of project performance using SS-curves,” *Journal of Construction Engineering and Management*, vol. 126, no. 2, pp. 142–148, 2000.

[34] H. Li and C. G. Soares, “Reliability analysis of floating offshore wind turbines support structure using hierarchical Bayesian network[C]//Proceedings of the 29th European Safety and Reliability Conference,” *Research Publishing Services Singapore*, pp. 2489–2495, 2019.