Design of a BIM-based Dynamic Monitoring and Audit Traceability System for Engineering Costs

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ABSTRACT Dynamic monitoring and audit traceability of engineering costs require integrated processing of BIM components, cost data, contract information, and construction progress. Traditional cost-management workflows based on manual quantity take-off and scattered documents have limited ability to support real-time control and complete audit paths. This study proposes a BIM-based dynamic monitoring and audit traceability system for engineering costs. A component-level mapping mechanism integrates bills of quantities, contract information, construction progress records, and cost items into a unified data structure. Based on BIM parametric modeling, quantities are automatically extracted, dynamic cost models are updated through timestamps and version control, and cost deviations are identified through planned-value, actual-cost, and deviation-value comparison. A schedule-cost coupling model is further introduced to detect abnormal cost changes caused by progress delays or rushed work. For traceability, a data-log and version-tracking mechanism records cost data generation, modification, and confirmation, while multi-source association auditing links components, business events, and cost results. Experiments show that cost-calculation time decreases from 128.5 s to 42.7 s, deviation identification increases to 92.8%, and audit-path completeness reaches 95.6%. The system supports BIM-based data integration, engineering monitoring, and traceable decision support.

INDEX TERMS bim technology, engineering cost monitoring, audit traceability, multi-source data integration, sensor data management

I. INTRODUCTION

WITH the expansion of project scale and the increase in management complexity, the management of project cost is shifting from static control to dynamic control of the entire process [1,2]. The existing model relies on two-dimensional drawings and decentralized data systems, which have problems such as data isolation, information update lag and insufficient collaboration among multiple participants, making it difficult to achieve real-time sharing of cost information and refined control [3]. In response to this situation, this paper constructs relevant methods based on BIM technology: using the BIM model as the core carrier, the integration of multi-source data such as bill of quantities, contract information and construction progress is realized, and a component-level mapping relationship is established to form a unified data foundation; relying on the parametric model, the quantity of work is automatically extracted, and a dynamic update mechanism for cost and cost deviation identification mechanism is constructed. The schedule-cost coupling analysis method is introduced to realize real-time monitoring of cost changes and trend judgment; on this basis, a data traceability and multi-source association audit traceability mechanism is designed to record the entire process of cost changes and restore the path.

II. RELATED WORK

Existing research explores the management of engineering projects from the perspective of digitalization and intelligence, forming a trend of technology integration with BIM, artificial intelligence and Internet of Things as the core. Parsamehr et al. reviewed the application of BIM in construction management, systematically analyzed the shortcomings of traditional management in data acquisition and decision support, and pointed out that BIM can significantly improve the level of schedule, cost, quality and safety management through digital modeling and predictive analysis, and built a decision support framework for the construction stage, providing a theoretical path for the informatization of engineering management [4]. On this basis, Obiuto et al. introduced artificial intelligence technology into the field of engineering management, optimized project planning and risk control through data analysis and machine learning methods. Case studies show that AI has obvious advantages in improving efficiency and reducing costs, but its promotion is still limited by factors such as data security and personnel acceptance [5]. In contrast, Rehman and Islam conducted a meta-analysis of IoT-related research based on the PRISMA framework, pointing out that technologies such as RFID and sensor networks have significant effects in reducing costs, shortening construction periods and reducing rework, but also exposed problems such as inconsistent indicator systems and uneven regional development, indicating that the application of a single technology path in complex engineering scenarios still has limitations [6]. Looking further ahead, the integration of multiple technologies and data-driven decision-making has gradually become a research focus. Sanusi proposed to integrate BIM, IoT and machine learning to achieve risk prediction and resource optimization. Practice has shown that this model can effectively reduce project delays and cost overruns, but it still faces challenges in data quality control, system integration and organizational transformation [7]. In addition, although Paul et al. focused on earthquake monitoring networks, their research on the integration of low-cost sensing devices and multi-source observation data provides a useful reference for data acquisition and collaborative analysis in complex engineering environments [8]. In summary, the above research shows that although the existing results have made positive progress in improving the efficiency and intelligence level of engineering management, there is still a lack of unified and systematic solutions in terms of deep integration of multi-source data, dynamic cost monitoring and full-process audit traceability. It is urgent to build an integrated method that integrates multiple technologies to support the development of engineering cost management towards refinement and transparency.

III. METHODS

A. BIM-DRIVEN COST DATA INTEGRATION METHOD

1) Multi-source data fusion and component-level mapping

Using the BIM model as the core carrier of engineering information, the bill of quantities, contract data, and construction progress information are integrated in a unified manner. First, multi-source data undergoes standardized coding processing to construct a unified identification system, denoting the component set as $(C = c_1, c_2, ..., c_n)$, the bill of quantities item set as $(Q = q_1, q_2, ..., q_m)$, and the cost item set as $(P = p_1, p_2, ..., p_k)$. Based on this, a mapping function is established between components, the bill of quantities, and costs:

$$f : C \to (Q, P) \tag{1}$$

To establish a link between model components and cost information.

Furthermore, based on the parametric features of the BIM model, the quantities of components are automatically extracted. Let (c_i) the quantity of a component be denoted as (V_i) and its corresponding unit price as (u_i). Then, the component cost can be expressed as:

$$\text{Cost}(c_i) = V_i \cdot u_i \tag{2}$$

Based on this, the total project cost can be obtained by summarizing all components:

$$C_{\text{total}} = \sum_{i=1}^{n} V_i \cdot u_i \tag{3}$$

Meanwhile, by embedding the pricing rules and payment constraints in the contract into the above model, the cost calculation is transformed from being driven by a single project quantity to a dual constraint mechanism of “project quantity - contract rules”, thereby improving the accuracy and consistency of data fusion.

2) Dynamic Data Update Mechanism

To address the dynamic changes in cost data during construction, a data update mechanism based on timestamps and version control is constructed. Let the project cost at a certain time (t) be (C(t)), then it can be represented as the cumulative cost of each component over time:

$$C(t) = \sum_{i=1}^{n} V_i(t) \cdot u_i(t) \tag{4}$$

Among them, $(V_i(t))$ represents the dynamic quantity of work that changes with the construction progress, and $(u_i(t))$ represents the dynamic unit price that is affected by contract changes or market factors. During the data update process, an incremental update strategy is introduced to represent the cost changes between adjacent time points as follows:

$$\Delta C = C(t) - C(t-1) \tag{5}$$

When design changes or on-site approvals occur, only the affected component set $(C' \subseteq C)$ is updated locally, thereby reducing system computational overhead and improving update efficiency.

In terms of data structure design, a dynamic relationship is constructed between “Planned Value (PV), Actual Value (AC), and Deviation Value (CV)”. The cost deviation is defined as:

$$CV = AC - PV \tag{6}$$

A value greater than zero (CV) indicates a cost overrun, while a value less than zero (CV) indicates a cost saving. This three-dimensional data structure enables continuous tracking and dynamic analysis of cost data over time. Furthermore, to ensure data traceability, a version function is introduced for each data update $(C^{(k)}(t))$, where (k) represents the (k)th update version. A new version is triggered automatically upon

the formal approval of design changes, site visas, or monthly progress settlements. This version sequence $(C^{(1)}, C^{(2)}, ..., C^{(k)})$ completely records the cost evolution process, providing a reliable basis for subsequent auditing and traceability by defining the completeness of the audit path as the ratio of captured version nodes to the total number of authorized change events.

B. METHODS FOR DYNAMIC MONITORING OF ENGINEERING COSTS

1) Automatic Quantity Extraction and Pricing Model

Leveraging the parametric features and semantic information of components in the BIM model, this system achieves integrated processing for automatic quantity extraction and cost calculation. By analyzing the geometric and material properties of components, it automatically identifies their corresponding quantity types (such as volume, area, or length) and matches them with quota items, forming a mapping relationship of "component—quantity—unit price." Based on this, the component quantities and corresponding unit prices are coupled for calculation, achieving automatic cost generation. Its basic expression is as follows:

$$C = \sum_{i=1}^{n} Q_i \cdot u_i \tag{7}$$

Where (Q_i) is the quantity of the (i)th component, (u_i) and is the corresponding unit price. This method can automatically update the cost results as the BIM model parameters change, thereby realizing the dynamic and real-time pricing process and avoiding the errors and lags caused by traditional manual measurement.

2) Cost Deviation Identification Method

During dynamic monitoring, cost deviations are identified and categorized by comparing planned and actual costs. Based on earned value management principles, a cost deviation indicator is introduced:

$$CV = AC - PV \tag{8}$$

Where (AC) represents the actual cost and (PV) represents the planned cost. A $(CV > 0)$ indicates a cost overrun, while a $(CV < 0)$ indicates a cost saving.

Based on this, and combined with a threshold control method, deviations are classified into different levels. Specifically, a 'deviation' is defined as any instance where the absolute value of CV exceeds 5% of the planned value (PV) for a component, or where the statistical outlier analysis identifies a cost change exceeding two

standard deviations from the historical mean. These are classified into levels such as normal fluctuations, slight deviations, and severe deviations, and their changing trends are analyzed through time series comparison. When the deviation continues to expand over multiple consecutive periods, it can be identified as an abnormal fluctuation, thereby triggering an early warning mechanism. This method can effectively identify and classify cost risks while ensuring computational simplicity.

3) Schedule-Cost Coupled Analysis Method

To reveal the impact mechanism of construction progress on project cost, a schedule-cost coupling analysis model is constructed. Under the earned value management framework, the value of completed work (EV) is introduced, and a cost performance index is constructed.

$$CPI = \frac{EV}{AC} \tag{9}$$

When CPI < 1, it indicates low cost efficiency and a risk of overspending; when CPI > 1, it indicates good cost control.

By linking progress tracking with cost analysis, abnormal cost changes caused by schedule delays or rush work can be identified. For example, when schedule deviations widen and the Cost Performance Index (CPI) continues to decline, it usually indicates reduced resource efficiency or inefficient construction organization. This method establishes an intrinsic link between schedule and cost, shifting cost risk from post-event control to pre-event prediction, thereby enhancing the foresight of dynamic monitoring of project costs.

C. AUDIT TRACEABILITY METHODS

1) Data Traceability and Version Tracking Mechanism

To achieve traceable management of the entire project cost process, a data logging and version tracking mechanism based on the BIM model is constructed to record the entire process of cost data generation, modification, and confirmation. Specifically, whenever cost data changes, the system automatically records the operation time, the operator, and the content of the change, and generates a corresponding data version identifier, thus forming a three-dimensional logging structure of "time-operation-content".

In terms of implementation, the BIM model serves as a unified data carrier, enabling version-based management of cost information at the component level. When design changes, engineering approvals, or measurement adjustments occur, the original data is not directly overwritten; instead, a new version is

created and historical records are retained, allowing for parallel storage of multiple versions. By constructing a version sequence, the evolution of cost data at different stages can be clearly reflected, providing a basis for subsequent responsibility identification and problem tracing. Simultaneously, an operation permission and log management mechanism is introduced to constrain and record the operational behaviors of different participating entities (such as the construction unit, contractor, and auditors). To handle concurrent updates in a multi-stakeholder environment, the system implements a pessimistic locking mechanism at the component level: when one participant initiates a modification, the specific component is locked to others until the version is committed or released. This ensures the standardization and controllability of the data change process while preventing data conflicts. This mechanism not only prevents data tampering and information loss but also provides complete process evidence in the event of cost disputes, thereby enhancing the transparency and credibility of the audit work.

2) Multi-source data correlation auditing method

Building upon data traceability, a multi-source data association auditing method is constructed to further improve audit efficiency and accuracy. Using BIM components as the core index unit, various business data generated during project implementation are linked and integrated, including design changes, site approvals, contract terms, and project payments, forming a multi-dimensional data association structure of "component —business event—cost result".

In practical implementation, a unified data association rule is established to bind each cost change to a corresponding business event. For example, when the quantity of a component changes, it can be traced back to whether it originated from a design change or on-site approval, and further linked to the relevant approval processes and contract terms, thus forming a complete audit path. This path not only reflects the result of cost changes but also reveals their causes and decision-making basis.

Furthermore, cross-referencing multi-source data can identify potential abnormal cost practices, such as duplicate measurements, insufficient justification for changes, or irregular payment procedures. Leveraging the visualization features of BIM models, audit results can be intuitively mapped onto 3D components, enabling precise problem localization and visual representation. This method transforms the traditional document-based audit approach into a data-driven, end-to-end audit model, effectively enhancing the systematic nature and traceability of the audit work.

IV. RESULTS AND DISCUSSION

A. EXPERIMENTAL DATA AND SAMPLE CONSTRUCTION

Actual engineering project data was selected as the basis for the experiment. Data sources included BIM model files, bills of quantities, construction progress records, contract pricing information, and change orders and payment records. The raw data was preprocessed, including format standardization, handling of missing values, and removal of outliers. The data was then reorganized according to the component level to form a cost dataset with BIM components as the basic unit.

In terms of sample segmentation, the data was divided into multiple time segments based on the construction stages to reflect the dynamic changes in cost data. Each time segment includes the corresponding stage's workload, cost expenditure, and schedule execution, thus constructing an experimental data system with time-series characteristics. Simultaneously, some typical components and key sub-items were selected as key analysis objects to enhance the representativeness of the experimental results.

B. EXPERIMENTAL PROCEDURE DESIGN

The experiment revolved around four stages: data integration, dynamic updates, monitoring and analysis, and audit traceability. First, pre-processed multi-source data was imported into the BIM model environment to complete component-level data mapping and initial cost calculation. Then, dynamic data was gradually introduced according to the construction progress to update the project quantity and cost information in stages, forming a continuous cost evolution sequence.

During the dynamic monitoring phase, cost data for each time segment is analyzed in real time to identify cost deviations and trends, and the monitoring results of key nodes are recorded. During the audit tracing phase, based on data traceability and multi-source correlation mechanisms, the identified abnormal cost data is traced back to locate the corresponding business events and responsible parties, forming a complete audit path record.

To ensure the repeatability of the experimental process, the operation procedures for each stage were standardized and the data input and processing rules were unified to ensure that the data between different time slices were comparable.

C. SETTING UP THE COMPARISON SCHEME

To verify the effectiveness of the constructed method in dynamic cost monitoring and audit traceability, a traditional method was set as the benchmark for comparison. The comparison scheme mainly adopts a conventional manual cost management workflow (CMW) as the baseline. This baseline utilizes AutoCAD for 2D geometry verification and Microsoft Excel-based spreadsheets for manual quantity take-off and pricing based on regional quota standards. It is characterized by the reliance on manual calculation for quantity extraction, typically performed in monthly cycles, and a lack of effective correlation between data due to the disconnected nature of paper-based site records and digital cost sheets.

Under identical data conditions, the proposed method and traditional methods were applied to the same engineering project, and their performance in terms of cost calculation efficiency, deviation identification capability, and audit traceability integrity was compared and analyzed. Unified data input and evaluation standards ensured the objectivity and consistency of the comparison results.

TABLE 1. Comparison of Cost Dynamic Monitoring Performance under Different Methods

Method Type	Traditional Method	Proposed Method
Cost Calculation Time (s)	128.5	42.7
Data Update Response Time (s)	95.2	18.9
Cost Deviation Detection Rate (%)	76.4	92.8
Average Delay in Deviation Detection (h)	12.6	3.4

As shown in Table 1, the proposed method demonstrates

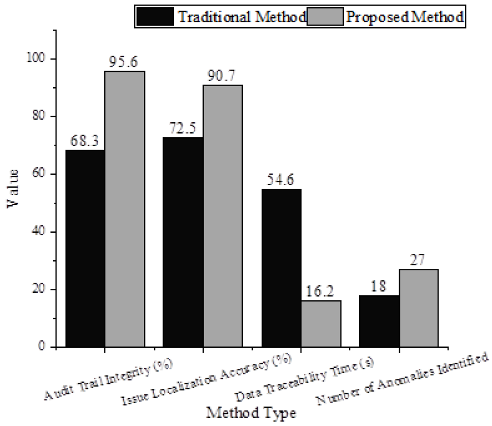

FIGURE 1. Comparison of Audit Traceability and Data Integrity

significant advantages over traditional methods in terms of dynamic monitoring performance of engineering costs. Firstly, in terms of computational efficiency, the cost calculation time is reduced from 128.5 s to 42.7 s, a decrease of approximately 66.8%, indicating that the BIM-based automatic quantity extraction and pricing model effectively reduces manual calculation and data processing time. Simultaneously, the data update response time is shortened from 95.2 s to 18.9 s, an improvement of over 80%, demonstrating that the constructed dynamic data update mechanism can achieve rapid synchronization and real-time feedback of cost information.

Secondly, in terms of monitoring accuracy and timeliness, the cost deviation identification rate of the method presented in this paper increased from 76.4% to 92.8%, an increase of 16.4 percentage points, indicating that the deviation identification and trend analysis method can more accurately capture abnormal cost changes; the average lag time for deviation identification was shortened from 12.6 h to 3.4 h, a reduction of about 73.0%, indicating that the method can detect potential cost risks earlier and realize the transformation from ex-post control to ex-ante warning.

As shown in Figure 1, the proposed method significantly improves upon traditional methods in terms of audit traceability and data integrity. Firstly, regarding audit path integrity, the accuracy increased from 68.3% to 95.6%, a rise of 27.3 percentage points. This indicates that the data association mechanism based on BIM components effectively integrates multi-source business information, constructing a more complete audit chain and avoiding the problem of missing key links. Secondly, in terms of problem location capability, the problem location accuracy increased from 72.5% to 90.7%, an improvement of 18.2 percentage points. This demonstrates that through data traceability and multi-source association methods, the source of cost anomalies and their corresponding business events can be traced more accurately, thereby improving the reliability and relevance of audit analysis. Simultaneously, the data traceability time was reduced from 54.6 seconds to 16.2 seconds, a decrease of approximately 70.3%, indicating that this method has a significant advantage in improving traceability efficiency, enabling rapid location and response.

V. CONCLUSION

This paper addresses the need for refined management of the entire engineering cost process and constructs a BIM-based method for dynamic cost monitoring and audit traceability. It achieves structured organization and real-time control of cost information through multi-source data integration, dynamic monitoring and analysis, and audit path construction. By using a component-level mapping mechanism and parametric models, automatic extraction of quantities and dynamic cost updates are achieved. Combined with cost deviation identification and schedule-cost coupling analysis methods, the accuracy and foresight of cost monitoring are improved. Simultaneously, a complete audit traceability chain is established through data logging and multi-source association mechanisms. Experimental results show that the proposed method outperforms traditional methods in terms of computational efficiency, deviation identification capability, and audit traceability completeness, effectively improving the real-time performance and transparency of engineering cost management. It should be noted that this research still has certain limitations. For example, the experimental data is mainly based on a single engineering scenario. To mitigate concerns regarding overfitting, a k-fold cross-validation approach was applied within the dataset stages, demonstrating consistent performance metrics across different construction phases. However, its applicability to different types of projects (residential, commercial, infrastructure) and complex environments has not been fully verified. Future research could further expand to diverse project typologies and multi-source heterogeneous data scenarios, combining intelligent algorithms to optimize deviation identification and risk prediction models to improve the system's generalization ability and intelligence level.

AUTHOR CONTRIBUTIONS

Zilin Zhou designed, collected and analyzed the data, and drafted the manuscript. Zilin Zhou conducted the study, critically revised the manuscript for important intellectual content, and gave final approval of the version to be published. Zilin Zhou participated fully in the work, take public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

CONFLICTS OF INTEREST

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