

Real-Time Construction Cost Control through BIM-Based Financial Digital Twins: A Framework for Predictive Budget Management

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ABSTRACT

This study aimed to develop and empirically evaluate a BIM-based financial digital-twin framework for real-time construction cost control by examining how BIM information integration, real-time data connectivity, automated financial synchronization, predictive cost analytics, early cost-variance detection, and decision-support capability contribute to predictive budget management and construction cost-control effectiveness. This applied, quantitative, cross-sectional study was conducted among construction professionals in Tehran, Iran. A total of 218 valid responses were obtained from project managers, BIM managers and coordinators, planning and project-control engineers, cost engineers, quantity surveyors, financial managers, construction managers, and consulting engineers with relevant experience in BIM, cost management, and digital construction. Data were collected using a structured questionnaire measuring BIM information integration, real-time data connectivity, automated financial synchronization, financial digital-twin capability, predictive cost analytics, early cost-variance detection, decision-support capability, predictive budget management, and construction cost-control effectiveness. The measurement and structural models were assessed using partial least squares structural equation modeling in SmartPLS, with reliability, convergent validity, discriminant validity, multicollinearity, path coefficients, effect sizes, explained variance, predictive relevance, and model fit examined. BIM information integration ($\beta = 0.286$, $p < 0.001$), real-time data connectivity ($\beta = 0.318$, $p < 0.001$), and automated financial synchronization ($\beta = 0.354$, $p < 0.001$) significantly predicted financial digital-twin capability. Financial digital-twin capability strongly predicted predictive cost analytics ($\beta = 0.647$, $p < 0.001$) and early cost-variance detection ($\beta = 0.423$, $p < 0.001$). Predictive cost analytics significantly improved decision-support capability ($\beta = 0.462$, $p < 0.001$), early cost-variance detection ($\beta = 0.391$, $p < 0.001$), and predictive budget management ($\beta = 0.437$, $p < 0.001$). Predictive budget management was the strongest direct predictor of construction cost-control effectiveness ($\beta = 0.521$, $p < 0.001$). The model explained 69.3% of the variance in predictive budget management and 71.8% of the variance in construction cost-control effectiveness, with satisfactory model fit (SRMR = 0.057). The findings demonstrate that BIM-based financial digital twins can substantially improve construction cost control when integrated project data are continuously synchronized and transformed into predictive financial intelligence, early variance warnings, and actionable managerial support, thereby enabling a shift from retrospective cost reporting toward proactive and real-time budget management.

Keywords: Building Information Modeling; Digital Twin; Construction Cost Control; Predictive Budget Management; Financial Digital Twin; Predictive Analytics; Real-Time Monitoring; PLS-SEM



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Introduction

The construction industry is increasingly characterized by complex project environments, fragmented supply chains, compressed schedules, volatile material prices, extensive subcontracting arrangements, and growing expectations for cost certainty, transparency, and accountability. Within this context, effective construction cost control has become substantially more difficult than the traditional comparison of planned and actual expenditure at periodic reporting intervals. Conventional cost-management approaches are frequently retrospective, relying on manually consolidated progress reports, accounting records, quantity measurements, spreadsheets, and delayed financial statements. Consequently, emerging deviations may remain undetected until they have already affected cash flow, procurement, productivity, or the final project budget. The digital transformation of the construction sector has therefore generated strong interest in technologies capable of linking physical project conditions with continuously updated digital information. Building Information Modeling (BIM), Internet of Things (IoT), artificial intelligence, digital twins, augmented and virtual reality, and Construction 4.0 platforms are increasingly being investigated as mechanisms for improving information integration, monitoring, forecasting, and decision-making across construction processes (1-3). These technologies create an important foundation for shifting cost management from periodic financial reporting toward real-time and predictive budget control.

BIM has been central to this digital transformation because it provides a structured digital representation through which geometric, technical, temporal, and financial project information can be integrated. In cost management, BIM supports automated quantity takeoff, improved cost estimation, linkage between work packages and model elements, scenario analysis, and better coordination between design and construction information (4). When BIM is incorporated into project-management processes, computational models can also be used to simulate alternative project solutions and assess their potential cost consequences before implementation (5). BIM has similarly demonstrated value in infrastructure development, where the technology supports design, engineering coordination, project execution, documentation, and lifecycle information management (6). Its broader integration into risk management and project execution further demonstrates that BIM can function as more than a visualization platform, particularly when information is connected with operational and managerial decision processes (7). Nevertheless, conventional BIM environments often remain static or periodically updated, meaning that their capacity for continuous financial monitoring is constrained unless they are connected with live project data and automated analytical systems.

The development of model-based construction has therefore progressed toward increasingly integrated digital environments. Research on the future of model-based construction indicates that BIM is likely to evolve through stronger automation, interoperability, cloud-based collaboration, real-time data exchange, and integration with emerging digital technologies (8). Similar developments are visible in smart-building contexts, where BIM provides the informational foundation for connecting design data, building systems, operational information, and smart-city applications (9). The integration of lean construction, BIM, and emerging technologies also demonstrates a trend toward coordinated digital workflows in which process efficiency, data visibility, and operational intelligence are combined within unified management systems (10). This evolution has important implications for financial management because the value of BIM in cost control increases considerably when the model can be dynamically synchronized with actual project progress, procurement commitments, resource consumption, accounting records, and cash-flow information.

Digital twin technology represents a further stage in this evolution by enabling continuous correspondence between physical construction processes and their digital representations. A digital twin is generally understood as a virtual representation of a physical asset, process, or system that is dynamically updated through data exchanges and can support monitoring, analysis, simulation, diagnosis, prediction, and decision-making. In built-environment research, digital twins have been distinguished from conventional digital models by their reliance on dynamic data exchange and their capacity to represent changing physical states rather than merely static design information (11). Reviews of digital twins in construction further indicate that BIM is a major enabling technology because it provides the information structure upon which real-time data can be organized and contextualized (12). Accordingly, the transition from BIM to digital twins can be viewed as a progression from information modeling toward continuous digital representation and feedback, in which the physical project and its virtual counterpart are increasingly synchronized.

Several technological enablers support this transition. IoT systems can continuously collect information on equipment status, environmental conditions, resource utilization, construction progress, asset performance, and site operations, thereby reducing dependence on manually generated project data. Low-cost IoT solutions have demonstrated that BIM-linked monitoring and management can be implemented through relatively accessible sensor infrastructures (13). In prefabricated construction, IoT has similarly been used to improve tracking, production coordination, logistics, quality management, and operational visibility (14). The integration of BIM and artificial intelligence of things has also been proposed for reconstruction and renovation contexts, illustrating how digital models and connected sensing environments can jointly support smarter and more responsive construction processes (15). In facilities management, the combination of BIM, employer information requirements, and IoT provides another example of how structured information and continuous data streams can be combined to improve asset and project management (16). Such integrations are directly relevant to cost control because physical events such as delayed activities, rework, material waste, equipment downtime, and productivity loss ultimately produce financial consequences that may be identified earlier when operational information is captured continuously.

The concept of a financial digital twin extends these principles to the economic state of a construction project. Rather than representing only physical geometry, progress, or asset condition, a financial digital twin would continuously associate real-world construction events with budget information, procurement commitments, invoices, payment certificates, actual expenditure, earned value, cash flow, forecast costs, and remaining financial exposure. In this sense, the financial twin would function as an evolving representation of the project's budget condition. Digital-twin applications in construction monitoring and control have already demonstrated the potential of synchronized digital environments to improve project visibility and reduce disruption under conditions of uncertainty (17). Digital twin and BIM technologies have also been used to support intelligent dispatching and management platforms, showing that project activities and resources can be monitored and coordinated through digitally integrated control architectures (18). These developments suggest that similar architectures can be adapted to financial management, where real-time cost information can be linked to operational data for earlier detection of budget deviations.

The growing literature on digital twins in construction management also highlights their role in anomaly detection and risk monitoring. Digital-twin systems can be designed to identify deviations from expected project behavior and provide managers with information about emerging risks before they become critical (19). This principle has direct relevance to cost variance, where deviations from planned expenditure, productivity, or resource consumption may

serve as early indicators of financial deterioration. More broadly, construction-management research has identified both substantial opportunities and implementation challenges associated with digital twins, including data integration, system interoperability, platform architecture, organizational capability, cost, and user acceptance (20). These challenges indicate that the effectiveness of a financial digital twin cannot be assumed merely because the underlying technologies are available. Instead, the system must be designed to ensure that data from BIM, site operations, procurement, accounting, and project controls are integrated in a consistent and managerially meaningful form.

The capability of digital twins to support lifecycle management further strengthens their relevance to financial control. Digital twin integration across the project lifecycle can improve data continuity, performance monitoring, decision support, and coordination from planning and construction through operation and renewal (21). BIM-enabled lifecycle governance likewise emphasizes the importance of maintaining reliable, reusable, and structured information throughout an asset's life, particularly for maintenance and renewal planning (22). Reviews of digital twins for existing bridge management have similarly shown that combining BIM, monitoring, and digital-twin concepts can support more effective lifecycle asset management (23). Advanced digital twins in bridge management further demonstrate how continuous structural monitoring can be integrated into digital representations to enable more informed and proactive management decisions (24). Although these applications are primarily technical and asset-oriented, they demonstrate a general principle that is equally applicable to financial management: dynamically updated project information can support earlier interventions and better forward-looking decisions.

The built-environment literature also emphasizes the importance of technological integration as a prerequisite for mature digital-twin systems. Digital-twin frameworks identify BIM, IoT, sensing technologies, data platforms, simulation, artificial intelligence, and interoperability as major enablers of dynamic digital environments (25, 26). The role of BIM in integrating digital twins is especially important because it provides the semantic and spatial structure required to connect diverse data sources to meaningful project components (12). The integration of IoT, virtual reality, and augmented reality into BIM-based facilities management further demonstrates how connected digital technologies can extend model-based information into more interactive and operationally responsive environments (27). Augmented reality research in construction similarly shows growing interest in digital interfaces that connect virtual information with physical project environments for visualization, monitoring, inspection, and management (28). For financial control, these developments imply that cost information can potentially be visualized and interpreted in direct association with physical components, work zones, and project activities rather than remaining isolated in conventional financial reports.

Artificial intelligence represents another important component of this transformation because it provides predictive and pattern-recognition capabilities that can extend digital twins beyond descriptive monitoring. AI-enabled digital-twin frameworks have been proposed for megaconstruction projects to integrate multidimensional information and improve lifecycle assessment, simulation, and decision-making (29). Construction research has also demonstrated how machine-learning methods can be connected with BIM information for cost optimization and prediction. The integration of BIM with an Elman neural network, for example, has shown the potential to enhance construction-cost forecasting by combining structured model data with intelligent predictive algorithms (30). More broadly, digital-twin environments can provide the continuous data infrastructure required for training, recalibrating, and applying predictive models. Recent work involving real and synthetic data in construction detection applications also illustrates the increasing sophistication of AI-supported construction analytics and the importance of managing

limited or imbalanced datasets in practical digital environments (31). In financial applications, similar analytical principles can be applied to predict cost-at-completion, identify abnormal expenditure patterns, forecast cash requirements, and estimate the probability of cost overrun.

The potential of digital twins to contribute to broader sustainability and performance objectives further reflects their analytical versatility. Digital-twin technologies have been increasingly applied in civil engineering to support sustainability, asset monitoring, performance optimization, and resource-efficient decision-making (32). Reviews of digital twins in construction have likewise emphasized their contribution to sustainable project delivery by improving information availability, operational efficiency, lifecycle performance, and data-driven management (33). In the building-energy domain, digital twins have been used for real-time monitoring, simulation, diagnosis, and performance optimization, although limitations related to data quality, computational complexity, interoperability, and model calibration remain important concerns (34). These limitations are equally relevant to financial digital twins because unreliable or poorly synchronized input data can produce inaccurate budget predictions and misleading management signals. Consequently, data quality, synchronization frequency, model validity, and interoperability must be treated as essential components of any framework for predictive budget management.

Digital-twin maturity is therefore a critical issue. The presence of BIM, sensors, or visualization tools does not necessarily indicate that a project has achieved a mature digital-twin capability. Maturity assessment approaches emphasize the need to evaluate the degree of integration among data sources, digital models, analytical functions, automation, organizational processes, and decision support (35). Similarly, BIM and digital-twin applications in prevention through design demonstrate that digital technologies create greater value when they are embedded within structured management processes rather than treated as standalone technical tools (36). Digital twins across the asset lifecycle face not only technical barriers but also organizational, economic, legal, and regulatory constraints related to data governance, responsibilities, costs, cybersecurity, interoperability, and standards (37). These challenges become especially important when financial information is involved, because accounting data, contractual records, procurement systems, and project-control information may be governed by different organizational units and data structures.

The gradual evolution from traditional asset-management systems toward BIM and digital twins also demonstrates the importance of information continuity. In cultural heritage management, the transition from conventional documentation methods to BIM and digital-twin systems has highlighted the benefits of integrated digital records, monitoring, and lifecycle information management (38). Comparable principles can be applied to construction cost management, where fragmented cost records can limit transparency and weaken the relationship between financial status and physical project progress. A financial digital twin can potentially overcome this fragmentation by establishing a digital thread connecting BIM objects, work breakdown structures, schedules, contracts, procurement packages, invoices, progress measurements, and budget data. This would allow changes in physical construction conditions to be translated into financial consequences in near real time.

Such integration is particularly important because cost overruns often emerge progressively rather than suddenly. Early deviations in productivity, quantities, procurement prices, schedules, or resource use may initially appear minor but can accumulate throughout the project. Traditional reporting systems may identify these patterns only after monthly or quarterly financial reconciliation. In contrast, a BIM-based financial digital twin could continuously calculate budgeted cost, actual cost, committed cost, remaining cost, forecast cost at completion, cost variance, and projected cash flow. It could therefore support a transition from reactive cost control to predictive

budget management. This orientation is consistent with the broader trajectory of Construction 4.0, which emphasizes connected information environments, automation, intelligent analytics, and decision-support systems (2). It is also aligned with research showing that BIM delivers greater organizational value when integrated with emerging technologies and process-management approaches rather than used as an isolated modeling application (3, 10).

Despite these developments, a notable research gap remains at the intersection of BIM-based cost management, digital twins, and predictive financial control. Existing studies have extensively examined BIM for estimating, simulation, design coordination, infrastructure management, safety, and smart-building development (4, 5, 9), while digital-twin research has emphasized monitoring, sustainability, lifecycle management, anomaly detection, facility management, and structural performance (19, 24, 32). However, comparatively less attention has been directed toward conceptualizing and empirically evaluating a financial digital twin in which BIM information, real-time data connectivity, automated financial synchronization, predictive analytics, variance detection, and decision support are integrated specifically for continuous budget control. The development of such a framework is particularly important because the managerial value of digital transformation ultimately depends on whether it enables project teams to identify financial problems earlier, forecast budget outcomes more accurately, and initiate corrective actions before cost overruns become irreversible.

Accordingly, the aim of this study was to develop and empirically evaluate a BIM-based financial digital-twin framework for real-time construction cost control by examining how BIM information integration, real-time data connectivity, automated financial synchronization, financial digital-twin capability, predictive cost analytics, early cost-variance detection, and decision-support capability contribute to predictive budget management and construction cost-control effectiveness.

Methods and Materials

This study employed an applied, quantitative, cross-sectional research design to develop and empirically evaluate a framework for real-time construction cost control through Building Information Modeling (BIM)-based financial digital twins, with particular emphasis on predictive budget management. The study population consisted of professionals involved in construction project planning, cost management, BIM implementation, project controls, financial management, quantity surveying, and digital construction in Tehran, Iran. Participants were recruited from Grade 1 and Grade 2 construction contractors, consulting engineering companies, project management organizations, BIM service providers, and major building and infrastructure projects operating in Tehran. To ensure that respondents possessed sufficient technical and managerial familiarity with the concepts examined in the study, eligibility criteria required participants to have at least three years of professional experience in the construction industry and direct experience with at least one of the following areas: BIM-based project delivery, construction cost estimation and control, project scheduling, earned value management, quantity surveying, financial monitoring, or digital project management. Individuals whose professional responsibilities were unrelated to project cost, BIM, or construction management were excluded. A total of 268 eligible professionals were approached using purposive and stratified convenience sampling to provide representation of different professional roles and organizational contexts. Of the distributed questionnaires, 231 were returned, and after screening for substantial missing values, patterned responses, and incomplete questionnaires, 218 valid responses were retained for the final analysis, corresponding to an effective response rate of 81.34%. The final sample included project managers, BIM managers

and coordinators, cost engineers, quantity surveyors, planning and project control engineers, financial managers, construction managers, and consulting engineers. The sample was considered adequate for multivariate modeling because it exceeded conventional minimum sample requirements for structural equation modeling and provided a sufficient respondent-to-parameter ratio for estimating the proposed conceptual model. Participation was voluntary, respondents were informed about the purpose of the research, confidentiality and anonymity were assured, and questionnaires were analyzed exclusively in aggregated form. The conceptual framework examined the integration of BIM information, real-time project data, automated cost synchronization, financial digital-twin capability, predictive analytics, and management decision support as mechanisms for improving budget forecasting, early detection of cost deviations, and proactive construction cost control.

Data were collected using a structured questionnaire developed specifically for the objectives of the study on the basis of the theoretical foundations of BIM, digital twins, construction cost management, predictive analytics, and real-time project control. The questionnaire consisted of two principal sections. The first section collected professional and organizational characteristics, including respondents' occupational position, educational qualification, years of construction-industry experience, experience with BIM applications, type of organization, principal project type, and level of involvement in project cost management. The second section assessed the major constructs incorporated into the proposed BIM-based financial digital-twin framework. These constructs included BIM information integration, real-time data connectivity, automated financial and cost synchronization, financial digital-twin capability, predictive cost analytics, early cost-variance detection, decision-support capability, predictive budget management, and overall construction cost-control effectiveness. Items were formulated to assess both the technological and managerial dimensions of the proposed framework. BIM information integration measured the extent to which quantities, design information, work breakdown structures, schedules, procurement information, and cost codes could be interconnected within a unified BIM environment. Real-time data connectivity assessed the capability to continuously incorporate information originating from site progress, procurement, resource consumption, accounting records, payment certificates, and project-control systems. Automated financial synchronization evaluated the automatic linkage between physical project progress and corresponding financial information, including committed costs, actual expenditures, budgeted costs, cash-flow information, and forecast costs. Financial digital-twin capability represented the ability of the system to maintain a continuously updated virtual financial representation of the project corresponding to changes in the physical construction process. Predictive cost analytics assessed the use of historical and real-time project data to forecast cost-at-completion, future cash requirements, probable cost overruns, and emerging budget risks. Early cost-variance detection assessed the ability of the proposed system to identify deviations between planned and actual financial performance before such deviations developed into significant cost overruns. Decision-support capability measured the extent to which financial digital-twin outputs could provide timely, interpretable, and actionable information for project managers. Predictive budget management and cost-control effectiveness represented the principal outcome dimensions of the framework and reflected improved forecast accuracy, accelerated identification of budget deviations, enhanced corrective decision-making, improved financial transparency, and stronger control over final project costs.

All construct items were measured on a five-point Likert scale ranging from 1, representing "strongly disagree," to 5, representing "strongly agree." Questionnaire development was conducted through a systematic multistage process. Initially, the relevant theoretical concepts and operational indicators were extracted from the BIM, digital-twin, construction cost-control, project-management, and predictive-analytics literature. The preliminary

questionnaire was then evaluated by a panel of 12 experts comprising university faculty members specializing in construction and project management, senior BIM specialists, project-control managers, and cost-management professionals with extensive experience in large construction projects. The experts examined the questionnaire for conceptual relevance, clarity, technical accuracy, redundancy, and correspondence between individual items and their intended constructs. Items identified as ambiguous or overlapping were revised, and terminology was adjusted to ensure consistency with professional construction-management practice in Iran. Content validity was subsequently assessed using expert judgment, and only items demonstrating acceptable relevance and clarity were retained. A pilot study involving 30 construction professionals who satisfied the primary inclusion criteria but were not included in the final sample was conducted to evaluate comprehensibility, questionnaire completion procedures, and preliminary internal consistency. Feedback obtained during the pilot stage resulted in minor modifications to wording without alteration of the conceptual structure of the instrument. Internal consistency reliability was assessed using Cronbach's alpha and composite reliability, while convergent validity was evaluated through standardized factor loadings and average variance extracted. Discriminant validity was assessed using the heterotrait-monotrait ratio and examination of inter-construct relationships. These psychometric assessments were performed before testing the structural relationships proposed in the BIM-based financial digital-twin framework.

In addition to questionnaire-based measurements, a BIM-based financial digital-twin prototype was conceptually configured to operationalize the proposed real-time cost-control process. The framework linked BIM model objects and quantities with project work breakdown structures, scheduling activities, cost codes, budget information, procurement commitments, actual expenditures, and physical progress records. The financial layer was designed to update project-cost status whenever changes occurred in quantities, progress percentages, procurement prices, resource consumption, or recorded expenditures. Cost information generated within this environment included budgeted cost, actual cost, committed cost, remaining cost, estimated cost at completion, cost variance, forecast variance at completion, and projected cash-flow requirements. The predictive component of the framework used accumulated project and financial information to estimate future budget performance and identify probable cost overruns. The integration of questionnaire evidence and the functional logic of the prototype made it possible to evaluate not only users' perceptions of the proposed technological framework but also the information architecture required for translating continuously updated BIM data into financial decision-support indicators.

Data analysis was conducted using IBM SPSS and SmartPLS software. Before hypothesis testing, the dataset was screened for missing observations, response irregularities, outliers, and distributional characteristics. Descriptive statistics, including frequencies, percentages, means, and standard deviations, were used to summarize respondents' professional characteristics and the observed distributions of the principal study variables. Multicollinearity among predictor constructs was examined using variance inflation factors, with values below 5 considered indicative of an acceptable level of collinearity. The measurement model was subsequently evaluated before assessment of structural relationships. Indicator reliability was examined using standardized outer loadings, with loadings of approximately 0.70 or greater regarded as preferable, although indicators with slightly lower values were retained where theoretically justified and where overall construct reliability remained satisfactory. Internal consistency was evaluated using Cronbach's alpha and composite reliability, for which coefficients of 0.70 or higher were considered acceptable. Convergent validity was assessed using average variance extracted, with values of at least 0.50 indicating that a construct explained an adequate proportion of the variance in its indicators.

Discriminant validity was examined primarily through the heterotrait-monotrait ratio, with values below 0.85 interpreted as evidence that conceptually distinct constructs demonstrated satisfactory empirical differentiation.

Partial least squares structural equation modeling was used to test the proposed relationships among BIM information integration, real-time data connectivity, automated financial synchronization, financial digital-twin capability, predictive cost analytics, decision-support capability, predictive budget management, and construction cost-control effectiveness. PLS-SEM was selected because the research was prediction-oriented, incorporated multiple latent constructs and mediated technological mechanisms, and sought to evaluate both the explanatory and predictive performance of an integrated digital cost-management framework. The explanatory power of the structural model was evaluated using the coefficient of determination for endogenous constructs, while predictive relevance was assessed through appropriate out-of-sample and predictive indicators. Path coefficients were estimated to determine the direction and magnitude of relationships among the latent variables. The statistical significance of direct and indirect effects was evaluated through bootstrapping with 5,000 resamples, using two-tailed tests and a significance level of $p < .05$. Effect sizes were examined to determine the practical contribution of individual exogenous constructs to the explained variance of endogenous variables rather than relying exclusively on statistical significance. Particular attention was given to the mediating roles of financial digital-twin capability and predictive cost analytics in converting BIM-enabled real-time project information into improved predictive budget management and more effective cost control. Model fit was additionally evaluated using the standardized root mean square residual, with values below 0.08 considered indicative of satisfactory approximate model fit. Finally, the relative importance of the framework components was examined by comparing standardized path coefficients, total effects, explained variance, and predictive performance. This analytical procedure enabled simultaneous evaluation of the measurement quality of the proposed constructs and empirical testing of the central proposition that integrating BIM with continuously synchronized financial information and predictive analytics can transform conventional retrospective cost monitoring into a proactive and real-time approach to construction budget management.

Findings and Results

A total of 218 valid questionnaires were included in the final analysis. The respondents represented a professionally experienced group of construction-industry specialists with direct involvement in BIM implementation, cost engineering, project controls, financial management, construction management, or related digital project-delivery activities in Tehran. Of the participants, 164 (75.2%) were male and 54 (24.8%) were female. In terms of age, 31 respondents (14.2%) were younger than 30 years, 82 (37.6%) were between 30 and 39 years, 69 (31.7%) were between 40 and 49 years, and 36 (16.5%) were aged 50 years or older. Regarding educational attainment, 49 participants (22.5%) held a bachelor's degree, 134 (61.5%) held a master's degree, and 35 (16.1%) held a doctoral or equivalent professional degree. Professional experience in the construction industry was also relatively high: 38 respondents (17.4%) reported 3–5 years of experience, 61 (28.0%) reported 6–10 years, 68 (31.2%) reported 11–15 years, and 51 (23.4%) had more than 15 years of experience. With respect to professional roles, 39 participants (17.9%) were project managers, 33 (15.1%) were BIM managers or coordinators, 37 (17.0%) were planning and project-control engineers, 32 (14.7%) were cost engineers or quantity surveyors, 27 (12.4%) were construction managers, 22 (10.1%) were financial or commercial managers, and 28 (12.8%) were consulting engineers or specialists in related project-management functions. Furthermore, 156 respondents (71.6%) reported

more than three years of direct experience using BIM-related technologies, while 137 (62.8%) had participated in projects in which BIM was linked, either partially or comprehensively, to scheduling, quantity takeoff, cost estimation, or financial-control processes. These demographic characteristics indicated that the sample contained an appropriate combination of managerial, technical, and financial expertise for evaluating a BIM-based financial digital-twin framework for real-time construction cost control.

Table 1. Descriptive Statistics of the Main Study Constructs

Construct	Number of Items	Mean	Standard Deviation	Minimum	Maximum	Skewness	Kurtosis
BIM Information Integration	5	3.91	0.67	1.80	5.00	-0.46	-0.18
Real-Time Data Connectivity	5	3.78	0.72	1.60	5.00	-0.38	-0.31
Automated Financial Synchronization	5	3.73	0.74	1.40	5.00	-0.35	-0.27
Financial Digital-Twin Capability	6	3.84	0.69	1.67	5.00	-0.42	-0.14
Predictive Cost Analytics	5	3.69	0.76	1.40	5.00	-0.31	-0.36
Early Cost-Variance Detection	4	3.88	0.70	1.50	5.00	-0.44	-0.12
Decision-Support Capability	5	3.92	0.68	1.60	5.00	-0.48	-0.06
Predictive Budget Management	5	3.86	0.71	1.40	5.00	-0.41	-0.21
Construction Cost-Control Effectiveness	5	3.95	0.66	1.80	5.00	-0.51	0.08

As shown in Table 1, the mean scores of all major constructs were above the midpoint of the five-point measurement scale, indicating generally favorable evaluations of the technological and managerial capabilities represented in the proposed framework. Construction cost-control effectiveness obtained the highest mean score ($M = 3.95$, $SD = 0.66$), followed closely by decision-support capability ($M = 3.92$, $SD = 0.68$) and BIM information integration ($M = 3.91$, $SD = 0.67$). These results suggested that respondents particularly recognized the potential value of integrating BIM information with financial data to support more effective managerial decisions and improve overall construction cost performance. Early cost-variance detection also received a relatively high evaluation ($M = 3.88$, $SD = 0.70$), indicating that the capacity to identify emerging financial deviations before they develop into substantial overruns was considered an important benefit of the proposed digital-twin architecture. Predictive budget management recorded a mean of 3.86 ($SD = 0.71$), while financial digital-twin capability had a mean of 3.84 ($SD = 0.69$), suggesting that respondents generally perceived continuously synchronized virtual financial representations of construction projects as both technically feasible and managerially useful. Real-time data connectivity ($M = 3.78$, $SD = 0.72$), automated financial synchronization ($M = 3.73$, $SD = 0.74$), and predictive cost analytics ($M = 3.69$, $SD = 0.76$) received somewhat lower, although still positive, mean scores. This pattern may reflect the greater technical and organizational complexity associated with continuous data exchange, automated linkage of physical progress and accounting information, and advanced forecasting analytics. Nevertheless, all average scores remained substantially above 3.00. Skewness values ranged from -0.31 to -0.51 and kurtosis values ranged from -0.36 to 0.08, showing no evidence of extreme distributional irregularity. The descriptive results therefore provided preliminary support for the suitability of the study variables for subsequent multivariate analysis and suggested broad professional acceptance of the proposed BIM-based financial digital-twin approach.

Table 2. Measurement Model Reliability and Convergent Validity Results

Construct	Outer Loading Range	Cronbach's Alpha	Composite Reliability	Average Variance Extracted	VIF Range
BIM Information Integration	0.742–0.864	0.879	0.912	0.675	1.42–2.38
Real-Time Data Connectivity	0.731–0.851	0.861	0.901	0.645	1.36–2.27
Automated Financial Synchronization	0.754–0.879	0.891	0.920	0.698	1.51–2.64
Financial Digital-Twin Capability	0.768–0.887	0.913	0.933	0.700	1.63–2.91
Predictive Cost Analytics	0.761–0.892	0.898	0.925	0.713	1.47–2.56
Early Cost-Variance Detection	0.783–0.891	0.872	0.913	0.725	1.39–2.24
Decision-Support Capability	0.749–0.881	0.886	0.917	0.689	1.44–2.48
Predictive Budget Management	0.776–0.903	0.905	0.930	0.728	1.52–2.73
Construction Cost-Control Effectiveness	0.781–0.895	0.901	0.927	0.718	1.49–2.67

The measurement-model results presented in Table 2 confirmed satisfactory reliability and convergent validity for all latent constructs included in the proposed framework. Standardized outer loadings ranged from 0.731 to 0.903, and therefore all retained indicators exceeded the generally recommended minimum level of approximately 0.70. The strongest indicator performance was observed for predictive budget management, for which outer loadings ranged from 0.776 to 0.903, whereas the lowest individual loading was 0.731 within the real-time data-connectivity construct. Cronbach's alpha coefficients ranged from 0.861 for real-time data connectivity to 0.913 for financial digital-twin capability, demonstrating strong internal consistency across all scales. Composite reliability values ranged from 0.901 to 0.933, and all exceeded the minimum recommended criterion of 0.70 without approaching levels that would suggest excessive indicator redundancy. Average variance extracted values ranged from 0.645 for real-time data connectivity to 0.728 for predictive budget management, with every construct exceeding the threshold of 0.50. Accordingly, each latent variable accounted for more than half of the variance in its associated indicators, providing clear evidence of convergent validity. Financial digital-twin capability demonstrated particularly strong reliability, with Cronbach's alpha of 0.913, composite reliability of 0.933, and AVE of 0.700, indicating that the items designed to represent continuous synchronization between physical project status and financial representation formed a coherent empirical construct. Predictive cost analytics, predictive budget management, and construction cost-control effectiveness also exhibited strong psychometric characteristics. Variance inflation factors ranged from 1.36 to 2.91, remaining well below the critical value of 5.00 and indicating that multicollinearity among indicators did not pose a significant problem. Collectively, these results demonstrated that the measurement model had sufficient reliability and convergent validity to support subsequent assessment of discriminant validity and structural relationships.

Table 3. Discriminant Validity Based on the Heterotrait-Monotrait Ratio

Construct	BII	RTD	AFS	FDT	PCA	ECVD	DSC	PBM	CCE
BIM Information Integration (BII)	—								
Real-Time Data Connectivity (RTD)	0.694	—							
Automated Financial Synchronization (AFS)	0.671	0.728	—						
Financial Digital-Twin Capability (FDT)	0.723	0.752	0.784	—					
Predictive Cost Analytics (PCA)	0.598	0.704	0.716	0.781	—				

Early Cost-Variance Detection (ECVD)	0.574	0.653	0.692	0.738	0.776	—			
Decision-Support Capability (DSC)	0.611	0.672	0.719	0.762	0.793	0.748	—		
Predictive Budget Management (PBM)	0.588	0.641	0.703	0.769	0.821	0.806	0.814	—	
Construction Cost-Control Effectiveness (CCE)	0.563	0.607	0.681	0.735	0.774	0.823	0.801	0.839	—

The HTMT values reported in Table 3 ranged from 0.563 to 0.839 and were therefore below the conservative threshold of 0.85 for all pairs of constructs. These findings confirmed that the latent variables incorporated into the proposed framework were empirically distinguishable despite their conceptual interrelationships. The highest HTMT coefficient was observed between predictive budget management and construction cost-control effectiveness (HTMT = 0.839), which was theoretically plausible because improvements in predictive budgeting were expected to contribute directly to the effectiveness of construction cost control. Nevertheless, the coefficient remained below the accepted discriminant-validity threshold, demonstrating that predictive budget management and cost-control effectiveness did not represent statistically redundant constructs. Other relatively strong relationships were observed between early cost-variance detection and construction cost-control effectiveness (HTMT = 0.823), predictive cost analytics and predictive budget management (HTMT = 0.821), and decision-support capability and predictive budget management (HTMT = 0.814). These relationships were consistent with the theoretical architecture of the financial digital-twin model, in which predictive analytics, deviation detection, decision support, and budget management were anticipated to function as interconnected but conceptually distinct components. The lower HTMT coefficients between upstream technological capabilities, such as BIM information integration, and downstream managerial outcomes further supported the multidimensional structure of the model. Therefore, the discriminant-validity assessment indicated that each construct captured a unique aspect of the BIM-based financial digital-twin framework and could appropriately be retained as a separate variable in structural-model testing.

Table 4. Structural Model and Hypothesis-Testing Results

Structural Relationship	β	t-value	p-value	Effect Size (f^2)	Result
BIM Information Integration → Financial Digital-Twin Capability	0.286	4.721	<0.001	0.112	Supported
Real-Time Data Connectivity → Financial Digital-Twin Capability	0.318	5.163	<0.001	0.139	Supported
Automated Financial Synchronization → Financial Digital-Twin Capability	0.354	5.894	<0.001	0.168	Supported
Financial Digital-Twin Capability → Predictive Cost Analytics	0.647	12.218	<0.001	0.718	Supported
Financial Digital-Twin Capability → Early Cost-Variance Detection	0.423	7.126	<0.001	0.246	Supported
Predictive Cost Analytics → Early Cost-Variance Detection	0.391	6.581	<0.001	0.211	Supported
Predictive Cost Analytics → Decision-Support Capability	0.462	8.204	<0.001	0.294	Supported
Early Cost-Variance Detection → Decision-Support Capability	0.301	5.337	<0.001	0.126	Supported
Predictive Cost Analytics → Predictive Budget Management	0.437	7.684	<0.001	0.267	Supported
Decision-Support Capability → Predictive Budget Management	0.352	6.147	<0.001	0.174	Supported
Early Cost-Variance Detection → Predictive Budget Management	0.219	3.879	<0.001	0.072	Supported
Predictive Budget Management → Construction Cost-Control Effectiveness	0.521	9.487	<0.001	0.382	Supported
Decision-Support Capability → Construction Cost-Control Effectiveness	0.247	4.286	<0.001	0.091	Supported
Early Cost-Variance Detection → Construction Cost-Control Effectiveness	0.196	3.512	<0.001	0.061	Supported

The structural-model results presented in Table 4 provided strong empirical support for all proposed relationships. Among the technological antecedents of financial digital-twin capability, automated financial synchronization exhibited the strongest standardized effect ($\beta = 0.354$, $t = 5.894$, $p < 0.001$), followed by real-time data connectivity ($\beta = 0.318$, $t = 5.163$, $p < 0.001$) and BIM information integration ($\beta = 0.286$, $t = 4.721$, $p < 0.001$).

This result indicated that establishing a financially meaningful digital twin depended not only on the existence of a detailed BIM model but, more importantly, on the capacity to continuously synchronize project progress, quantities, accounting records, commitments, expenditures, and budget information. Financial digital-twin capability subsequently exerted a strong positive effect on predictive cost analytics ($\beta = 0.647$, $t = 12.218$, $p < 0.001$), representing the largest path coefficient in the structural model. Its effect size was also substantial ($f^2 = 0.718$), indicating that continuously updated digital representation constituted a central enabling mechanism for predictive financial analysis. Financial digital-twin capability was also positively associated with early cost-variance detection ($\beta = 0.423$, $t = 7.126$, $p < 0.001$). Predictive cost analytics, in turn, significantly enhanced early cost-variance detection ($\beta = 0.391$, $p < 0.001$), decision-support capability ($\beta = 0.462$, $p < 0.001$), and predictive budget management ($\beta = 0.437$, $p < 0.001$). These relationships demonstrated that prediction-oriented processing of real-time financial and project data contributed not merely to more accurate forecasts but also to earlier identification of adverse budget patterns and stronger managerial interpretation of project-cost conditions. Decision-support capability had a significant effect on predictive budget management ($\beta = 0.352$, $p < 0.001$), while early cost-variance detection also contributed directly to predictive budget management ($\beta = 0.219$, $p < 0.001$). Finally, predictive budget management was the strongest direct determinant of construction cost-control effectiveness ($\beta = 0.521$, $t = 9.487$, $p < 0.001$), with a substantial effect size of $f^2 = 0.382$. Decision-support capability ($\beta = 0.247$, $p < 0.001$) and early cost-variance detection ($\beta = 0.196$, $p < 0.001$) also demonstrated statistically significant direct effects on cost-control effectiveness. Overall, the pattern of structural coefficients supported a sequential mechanism in which integrated BIM information, real-time connectivity, and automated financial synchronization establish the foundation for a financial digital twin; the digital twin then enables predictive analytics and timely identification of deviations; and these capabilities ultimately strengthen predictive budget management and construction cost-control performance.

The explanatory performance of the structural model was also substantial. BIM information integration, real-time data connectivity, and automated financial synchronization jointly explained 64.8% of the variance in financial digital-twin capability ($R^2 = 0.648$). Financial digital-twin capability explained 41.9% of the variance in predictive cost analytics ($R^2 = 0.419$). Financial digital-twin capability together with predictive cost analytics explained 58.7% of the variance in early cost-variance detection ($R^2 = 0.587$). Predictive cost analytics and early cost-variance detection collectively accounted for 55.6% of the variance in decision-support capability ($R^2 = 0.556$). Predictive cost analytics, decision-support capability, and early cost-variance detection explained 69.3% of the variance in predictive budget management ($R^2 = 0.693$), while predictive budget management, decision-support capability, and early cost-variance detection jointly explained 71.8% of the variance in construction cost-control effectiveness ($R^2 = 0.718$). These coefficients demonstrated moderate-to-substantial explanatory power, particularly for the two principal managerial outcomes of predictive budget management and cost-control effectiveness. Predictive-relevance coefficients obtained through blindfolding procedures were greater than zero for all endogenous variables, including financial digital-twin capability ($Q^2 = 0.421$), predictive cost analytics ($Q^2 = 0.286$), early cost-variance detection ($Q^2 = 0.397$), decision-support capability ($Q^2 = 0.368$), predictive budget management ($Q^2 = 0.492$), and construction cost-control effectiveness ($Q^2 = 0.516$). The standardized root mean square residual was 0.057, remaining below the recommended maximum value of 0.08 and indicating satisfactory approximate model fit. Thus, the structural model demonstrated both strong explanatory capacity and meaningful predictive relevance.

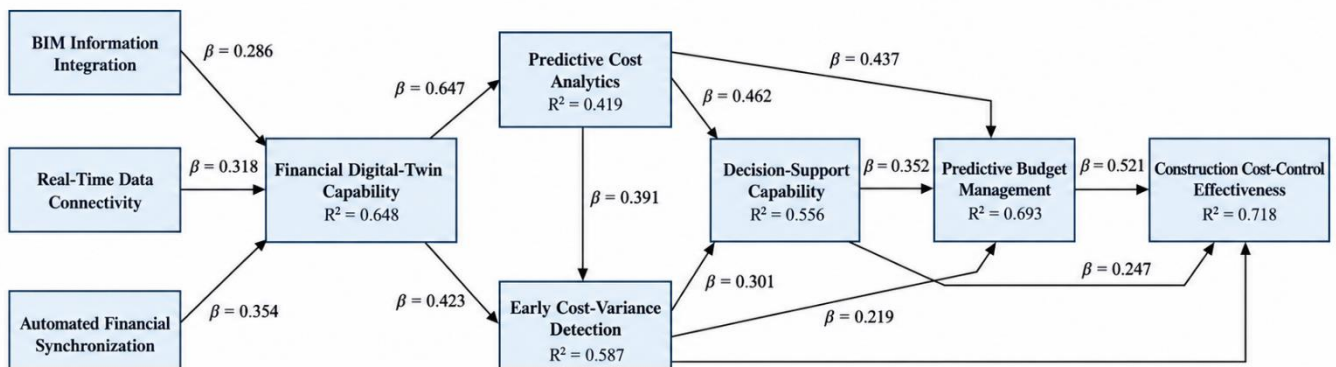


Figure 1. Structural Model of BIM-Based Financial Digital Twins for Predictive Budget Management and Real-Time Construction Cost Control

The structural pattern illustrated in Figure 1 demonstrates the progressive transformation of project information into financially actionable intelligence within the proposed digital-twin framework. The strongest upstream contribution to financial digital-twin capability originated from automated financial synchronization ($\beta = 0.354$), although real-time data connectivity ($\beta = 0.318$) and BIM information integration ($\beta = 0.286$) also made significant contributions. Once the digital-twin capability was established, its dominant effect was on predictive cost analytics ($\beta = 0.647$), confirming that a continuously updated financial representation of the construction project provided the informational basis required for forward-looking financial forecasts. Predictive cost analytics subsequently contributed to early cost-variance detection, managerial decision support, and predictive budget management, thereby functioning as a central intermediary between the digital representation of the project and managerial cost-control outcomes. The model further showed that predictive budget management served as the most important immediate driver of construction cost-control effectiveness ($\beta = 0.521$), while decision-support capability and early detection of cost deviations exerted additional direct effects. The explained variance of 69.3% for predictive budget management and 71.8% for construction cost-control effectiveness demonstrated that the model captured a substantial proportion of the factors underlying proactive financial management in construction projects. Taken together, the figure indicates that the principal advantage of a BIM-based financial digital twin lies not merely in digitizing existing cost records but in establishing a continuous information chain from design and physical progress through financial synchronization and predictive analysis to proactive budget decisions. The results therefore support the central proposition of the study that construction cost control can be shifted from periodic and retrospective reporting toward a dynamic, data-driven, and predictive management process when BIM data, real-time project information, financial systems, and predictive analytics are integrated within a unified digital-twin architecture.

Further examination of indirect effects confirmed the mediating mechanisms proposed in the framework. BIM information integration had a significant indirect effect on predictive budget management through financial digital-twin capability and predictive cost analytics ($\beta = 0.081$, $t = 3.917$, $p < 0.001$), while real-time data connectivity demonstrated a slightly stronger indirect effect through the same pathway ($\beta = 0.090$, $t = 4.228$, $p < 0.001$). Automated financial synchronization produced the strongest corresponding indirect effect on predictive budget management ($\beta = 0.100$, $t = 4.614$, $p < 0.001$). Similarly, financial digital-twin capability exerted a significant indirect effect on construction cost-control effectiveness through predictive cost analytics, decision-support capability, early

cost-variance detection, and predictive budget management. The total indirect effect of financial digital-twin capability on cost-control effectiveness was $\beta = 0.361$ ($t = 7.438$, $p < 0.001$), demonstrating that the managerial benefits of the digital twin were transmitted primarily through its analytical and predictive functions rather than through technological representation alone. Predictive cost analytics also demonstrated a significant total indirect effect on construction cost-control effectiveness ($\beta = 0.298$, $t = 6.019$, $p < 0.001$), largely through improvements in predictive budget management and decision-support capability. These mediation results reinforce the interpretation that technological integration by itself is insufficient to achieve substantial cost-control improvements; rather, integrated and synchronized information must be transformed into forecasts, deviation warnings, and actionable management information before it can materially affect budget performance. Overall, the findings supported the complete conceptual sequence underlying the proposed framework and demonstrated that BIM-based financial digital twins can provide an empirically coherent foundation for predictive and real-time construction budget management.

Discussion and Conclusion

The present study developed and empirically evaluated a BIM-based financial digital-twin framework for real-time construction cost control and predictive budget management. The findings demonstrated that BIM information integration, real-time data connectivity, and automated financial synchronization significantly strengthened financial digital-twin capability, which subsequently enhanced predictive cost analytics, early cost-variance detection, decision-support capability, predictive budget management, and ultimately construction cost-control effectiveness. The structural model showed particularly strong explanatory power for predictive budget management and cost-control effectiveness, with R^2 values of 0.693 and 0.718, respectively. These results indicate that the proposed framework captures a substantial proportion of the mechanisms through which digitally integrated project information can improve financial control in construction. The findings also showed that predictive budget management was the strongest direct determinant of construction cost-control effectiveness, while financial digital-twin capability exerted its most substantial direct effect on predictive cost analytics. Taken together, the results support a sequential interpretation in which the technological integration of project information becomes managerially valuable only when it is transformed into continuously updated financial representations, predictive analyses, early warnings, and actionable decision support.

The positive effect of BIM information integration on financial digital-twin capability was consistent with the theoretical role of BIM as the principal information backbone of digitally enabled construction management. The significant path from BIM information integration to financial digital-twin capability indicated that the ability to connect quantities, work breakdown structures, schedules, cost codes, procurement data, and model objects is essential for constructing a financially meaningful digital representation of a project. This finding aligns with studies emphasizing the role of BIM in construction cost management, particularly through the integration of quantity information, cost estimation, and project-management data (4, 5). It is also consistent with evidence that BIM provides a foundational data structure for digital-twin development because it organizes project information spatially and semantically before live data can be incorporated (12). The present result therefore suggests that a financial digital twin cannot function effectively if BIM remains limited to geometric visualization or design coordination. Instead, BIM must be structured in a way that supports reliable linkage between technical project elements and their financial attributes.

Real-time data connectivity also had a significant positive effect on financial digital-twin capability, demonstrating that the digital twin depends on continuous or near-real-time information exchange rather than periodic manual updates. This result is consistent with the broader digital-twin literature, which distinguishes digital twins from static digital models primarily through dynamic synchronization with physical systems (11). The finding is also aligned with the use of IoT-supported BIM environments for monitoring, analysis, and management, where continuous sensor and operational data enable digital representations to reflect changing real-world conditions (13). Similar conclusions have been reported in prefabricated-building research, where IoT integration improves tracking, logistics, production visibility, and operational coordination (14). In the context of the present study, the implication is that financial control becomes more responsive when physical progress, procurement activities, site resource consumption, and cost transactions are captured without substantial reporting delays. Real-time data connectivity therefore functions as the bridge between physical construction processes and their financial consequences.

Among the technological antecedents, automated financial synchronization had the strongest effect on financial digital-twin capability. This was an important result because it demonstrates that the most critical step in building a financial digital twin is not simply collecting more project data but ensuring that physical project changes are systematically translated into financial updates. Automated financial synchronization creates a direct connection between work progress, quantities, commitments, actual expenditures, remaining cost, and budget forecasts. The result is consistent with the broader logic of integrated digital platforms, in which BIM, IoT, and structured information requirements are linked to support coordinated asset and project management (16). It also corresponds with research on BIM-integrated smart environments, where the value of digitalization depends on interoperable information flows rather than isolated software applications (9, 10). The strong coefficient found in this study suggests that organizations seeking to implement financial digital twins should prioritize automated financial linkages across BIM, enterprise systems, project-control databases, and accounting platforms.

Financial digital-twin capability exerted the strongest direct effect in the model on predictive cost analytics. This finding supports the central proposition that continuously synchronized project representations are valuable because they provide the data foundation required for forward-looking financial analysis. A financial digital twin does not merely summarize current cost status; rather, it creates a continuously updated dataset from which future expenditure, cost-at-completion, cash-flow requirements, and probability of overrun can be estimated. This result is consistent with research on digital twins as platforms for simulation, prediction, and decision support across the project lifecycle (21, 26). It also aligns with studies integrating BIM and intelligent algorithms for construction cost prediction, which show that model-based data can improve the analytical basis for forecasting and optimization (30). The present findings extend this literature by suggesting that predictive cost analytics becomes substantially more powerful when it is embedded within a continuously updated digital-twin architecture rather than applied to static or periodically collected datasets.

The significant relationship between financial digital-twin capability and early cost-variance detection further demonstrated the practical value of continuous digital synchronization. The result indicates that when budget, progress, procurement, and expenditure information are updated in near real time, project teams are better able to identify deviations before they become severe. This finding is compatible with previous digital-twin research emphasizing anomaly detection and risk identification. Digital-twin systems have been used to detect abnormal conditions and support risk systematization in smart-building and construction environments (19). The same underlying principle applies to financial performance: a deviation from expected expenditure or resource behavior

can be treated as an anomaly that warrants managerial attention. Digital twins developed for construction monitoring and control have similarly been associated with improved visibility and responsiveness under uncertain project conditions (17). The current findings therefore provide empirical support for extending anomaly-detection concepts from physical and operational parameters to cost and budget indicators.

Predictive cost analytics had significant positive effects on early cost-variance detection, decision-support capability, and predictive budget management. These results suggest that forecasting is not an isolated analytical activity but a mechanism through which managers can interpret emerging project conditions and respond proactively. Predictive analytics enables the identification of patterns that are not always visible through conventional variance reporting, particularly when multiple variables such as progress, procurement, productivity, quantity change, and expenditure interact over time. This is aligned with AI-enabled digital-twin research, which emphasizes the capacity of intelligent analytics to enhance simulation, assessment, and decision-making in complex construction environments (29). More broadly, recent digital-construction research demonstrates increasing use of AI and data-driven approaches for identifying and predicting construction conditions from complex datasets (31). The present study extends this logic into financial management by showing that predictive cost analytics contributes simultaneously to detecting budget risks, strengthening decision support, and improving the quality of future budget projections.

The positive effect of early cost-variance detection on decision-support capability and predictive budget management further emphasizes the managerial importance of timeliness. A cost deviation that is identified after it has already been absorbed into project performance provides limited opportunity for corrective action. In contrast, early detection allows project managers to revise procurement strategies, reallocate resources, renegotiate subcontracting arrangements, adjust schedules, control scope, or revise cash-flow plans before financial deterioration accelerates. This interpretation is consistent with construction-management research showing that digital twins can support more proactive monitoring and intervention by reducing the time between a physical event and its managerial interpretation (18, 20). It also reflects the broader principles of Construction 4.0, where connected technologies are expected to enable faster, more data-driven management responses (2). Thus, the value of digital cost control appears to depend not only on analytical accuracy but also on how rapidly relevant signals become available to decision-makers.

Decision-support capability significantly improved predictive budget management, indicating that digital information must be translated into actionable managerial outputs before it can generate substantial budgetary benefits. This finding is important because digital transformation initiatives can fail when they generate large volumes of data without improving decision quality. The result aligns with literature showing that BIM and digital twins create greater value when integrated into project-management and governance processes rather than treated as standalone technical systems (1, 22). It is also consistent with work on digital-twin maturity, which emphasizes that mature implementation involves not only data integration but also analytical capabilities, process alignment, and organizational use of digital outputs (35). Therefore, the present study suggests that dashboard design, alert mechanisms, forecast interpretation, and managerial workflows are as important as the underlying technological infrastructure.

The strongest direct determinant of construction cost-control effectiveness was predictive budget management. This result suggests that cost-control performance improves most when organizations move from static budget comparison toward continuous forecasting of future financial outcomes. Predictive budget management allows

managers to evaluate likely cost-at-completion, anticipated cash requirements, exposure to overruns, and the financial consequences of current project trends. The result is consistent with BIM-based cost-optimization research emphasizing the benefits of using computational models to support financial planning and scenario evaluation (5). It also aligns with intelligent BIM-based cost prediction approaches that demonstrate the value of integrating structured project information with predictive algorithms (30). The present study goes further by showing that predictive budget management serves as the main mechanism translating digital-twin capabilities into improved cost-control effectiveness.

Decision-support capability and early cost-variance detection also exerted significant direct effects on construction cost-control effectiveness. These findings indicate that effective financial control results from a combination of prediction, interpretation, and timely intervention. Predictive budget management may provide the strongest overall effect, but its practical value is reinforced when decision-makers receive clear information and warnings about emerging deviations. This interpretation is compatible with research on digital-twin applications in infrastructure monitoring, where the ultimate benefit lies in supporting timely interventions based on continuous condition assessment (23, 24). Although those studies focus mainly on structural and asset-management applications, the same decision logic applies to financial control: continuous monitoring becomes valuable when it changes managerial action.

The substantial R^2 values obtained for predictive budget management and construction cost-control effectiveness further demonstrated the explanatory adequacy of the proposed framework. The model explained 69.3% of the variance in predictive budget management and 71.8% of the variance in cost-control effectiveness. These values indicate that the integrated digital and managerial capabilities examined in the study provide a strong explanation of financial-control performance. This result supports previous arguments that the greatest benefits of BIM and digital twins emerge through integration with complementary technologies and managerial systems (3, 10). It also supports the perspective that digital twins should be treated as lifecycle information systems rather than isolated visualization tools (37). The model fit and positive predictive-relevance values further indicated that the proposed framework was not only statistically coherent but also capable of capturing meaningful variation in the principal outcomes.

The mediation results add further insight into the mechanism underlying the framework. BIM information integration, real-time data connectivity, and automated financial synchronization affected predictive budget management indirectly through financial digital-twin capability and predictive cost analytics, while financial digital-twin capability influenced cost-control effectiveness primarily through downstream analytical and managerial processes. This pattern indicates that technological implementation alone is unlikely to produce substantial financial benefits unless it generates usable analytical intelligence. The finding aligns with research showing that digital-twin adoption faces organizational and implementation challenges beyond the technical availability of tools (37). It also corresponds with evidence from digital-twin applications in energy, facilities management, and built-environment systems, where data quality, interoperability, model calibration, and managerial integration determine whether digital platforms produce meaningful performance improvements (27, 34). Thus, the financial benefits of digital twins appear to arise from an integrated chain of capabilities rather than from technology adoption in isolation.

The results also have broader implications for the ongoing transition from BIM toward more advanced digital construction ecosystems. BIM-based project environments are increasingly connected with IoT, AI, augmented reality, and lifecycle management systems (15, 28). Digital-twin frameworks similarly identify interoperability, real-

time data exchange, visualization, and analytics as key enablers (25, 26). The present study contributes to this evolution by positioning financial data as a core component of the digital twin rather than a peripheral reporting layer. This is particularly relevant because construction decisions are ultimately constrained by budget availability and financial performance. Integrating cost information into the digital thread therefore expands the digital twin from a technical monitoring system into a project-governance mechanism capable of supporting both operational and financial decisions.

The findings are also consistent with broader evidence that BIM and digital technologies can enhance efficiency, coordination, sustainability, and lifecycle performance when implemented through integrated management structures (32, 33). Moreover, the use of digital twins in heritage, infrastructure, and facilities management demonstrates that synchronized digital environments can support complex decisions across different asset types and lifecycle stages (6, 36, 38). The present study extends this body of knowledge by demonstrating that similar principles can be applied specifically to real-time financial control. Overall, the results indicate that a BIM-based financial digital twin can shift cost management away from delayed retrospective reporting and toward continuous, predictive, and intervention-oriented budget governance.

The present study has several limitations that should be considered when interpreting the findings. First, the research was conducted using a cross-sectional sample of construction professionals from Tehran, and therefore the results may not fully represent organizational practices, digital maturity levels, or regulatory environments in other regions or countries. Second, the study relied primarily on self-reported perceptions of BIM, digital-twin capability, predictive analytics, and cost-control effectiveness, which may be influenced by respondent experience, organizational culture, or subjective expectations regarding digital technologies. Third, although the conceptual framework incorporated a wide range of technological and managerial variables, other factors such as organizational digital maturity, contractual arrangements, project complexity, cybersecurity readiness, data-governance capability, and top-management support were not explicitly modeled. Finally, the proposed financial digital-twin architecture was evaluated through survey-based structural modeling rather than longitudinal observation of complete project lifecycles, meaning that the causal sequence identified in the model should be interpreted cautiously.

Future research should examine the proposed framework in larger and more diverse samples covering different project types, regions, contracting environments, and levels of digital maturity. Longitudinal studies would be particularly valuable for investigating how financial digital twins influence actual project cost performance over time and whether predictive accuracy improves as more real-time data become available. Future studies could also integrate objective project datasets, including BIM quantities, earned-value indicators, procurement records, invoices, progress data, and actual final costs, to validate the relationships identified through survey evidence. Comparative analyses across infrastructure, residential, commercial, industrial, and megaproject contexts could determine whether the strength of the proposed relationships varies according to project complexity. Additional studies could investigate the moderating roles of organizational readiness, data quality, contractual integration, cybersecurity capability, and user competence, while machine-learning approaches could be tested for improving cost-at-completion forecasting, anomaly detection, and dynamic budget-risk classification.

From a practical perspective, construction organizations should implement financial digital twins incrementally, beginning with the establishment of reliable BIM cost structures and standardized links among model objects, work breakdown structures, schedules, procurement packages, and accounting codes. Organizations should prioritize

automated data exchange among BIM platforms, enterprise resource planning systems, project-control applications, procurement databases, and site-monitoring technologies so that physical project changes are rapidly reflected in financial indicators. Project teams should also develop real-time dashboards that emphasize forecast cost, committed cost, variance trends, cash-flow exposure, and early-warning indicators rather than relying exclusively on historical expenditure reports. Dedicated governance procedures should be established for data validation, system ownership, access control, and responsibility for responding to financial alerts. Finally, managers should ensure that personnel in BIM, cost engineering, finance, procurement, and project controls work within an integrated digital workflow so that predictive outputs are translated into timely corrective decisions rather than remaining isolated analytical results.

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Authors' Contributions

All authors equally contributed to this study.

Declaration of Interest

The authors of this article declared no conflict of interest.

Ethical Considerations

All ethical principles were adhered in conducting and writing this article.

Transparency of Data

In accordance with the principles of transparency and open research, we declare that all data and materials used in this study are available upon request.

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