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Integrating BIM Level 3 Digital Twin and Earned Value Management for Multi-Storey Building Cost and Time Control

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ABSTRACT

Cost overruns and schedule delays persist in multi-storey building construction, where project control often relies on periodic manual progress assessment and spreadsheet-based Earned Value Management (EVM). This study develops an integrated framework combining BIM Level 3 (digital twin) with EVM to improve the accuracy and timeliness of cost and schedule monitoring. The framework was applied to a 12-storey reinforced-concrete office tower in Padang City, West Sumatra (budget IDR 78.5 billion, planned duration 78 weeks). A federated IFC model was synchronized with as-built data from terrestrial laser scanning, RFID tags, and progress cameras to compute Earned Value automatically, and was compared with conventional manual EVM at eight control points against an independent verified quantity survey. The digital-twin approach reduced the mean absolute percentage error of progress measurement from 11.1% to 1.4%, shortened the reporting cycle from about 120 to 4 hours, and detected the adverse cost trend about 35 weeks earlier. Early detection enabled corrective action that limited the final cost overrun to 3.8% of the budget, against 11.2% forecast under conventional monitoring. Integrating BIM Level 3 digital twins with EVM therefore provides a more accurate, timely, and actionable basis for cost and schedule control.

Keywords: *Building Information Modelin, BIM Level 3, Digital Twin, Earned Value Management, Cost Control, Schedule Performance, Multi-Storey Building*

INTRODUCTION

Multi-storey building construction projects are characterized by high capital intensity, complex trade coordination, and compressed schedules, all of which make them particularly vulnerable to cost overruns and time delays. Industry-wide statistics compiled for the 2020-2024 period indicate that average cost overruns in construction projects consistently exceed 20%, while schedule deviations approach 30%, underscoring the limited effectiveness of traditional, document-based project control methods once execution begins. In the Indonesian context, multi-storey building projects frequently

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experience similar performance gaps, driven by fragmented information flows between design, cost, and schedule functions, and by the continued reliance on periodic manual progress assessment (commonly referred to as opname) to update project control records.

Earned Value Management (EVM) has long been recognized as an effective technique for integrating cost and schedule control, providing standardized indices, namely the Cost Performance Index (CPI) and Schedule Performance Index (SPI), that quantify project efficiency relative to the baseline plan. However, a recent review of EVM practice in construction noted that many firms continue to rely on fragmented systems for cost control, scheduling, and procurement, limiting the responsiveness and accuracy of EVM outputs, and that resistance to change and a shortage of trained personnel remain significant barriers to more advanced implementation. Building Information Modeling (BIM), by contrast, has matured into a widely adopted digital framework for lifecycle management, design coordination, and, at more advanced maturity levels, cost and schedule simulation through 4D (time) and 5D (cost) model dimensions.

The convergence of BIM with cyber-physical sensing technologies has given rise to the concept of the BIM-enabled digital twin, commonly associated with BIM Level 3 maturity, in which a federated, cloud-based model is continuously synchronized with real-world sensor data to create a bi-directional link between the physical asset and its digital representation. Deng, Menassa and Kamat (2021), in a systematic review of 123 studies, proposed a five-level maturity ladder for BIM-to-digital-twin evolution, ranging from basic BIM visualization (Level 1) through BIM-supported simulation (Level 2), BIM-IoT integration for real-time monitoring (Level 3), BIM-AI integration for prediction (Level 4), to fully automated control (Level 5); their review found that most existing implementations remain concentrated at Levels 2-3, with significant gaps persisting in real-time simulation and data interoperability at higher maturity levels. Lu et al. (2020) similarly framed the transition from static BIM models to dynamic digital twins as a strategic pathway for smart asset management, while Megahed and Hassan (2022) characterized this evolution as a paradigm shift for the post-pandemic architecture, engineering, construction, and operations (AECO) industry. More recently, Alnaser et al. (2024) developed an assessment framework for BIM-digital-twin readiness in the construction industry, finding that cost optimization and resource management were pivotal factors influencing successful adoption, alongside organizational readiness and availability of skilled operators.

A separate but complementary strand of research has explored the direct integration of EVM with BIM. Early computational tools such as COST-BIM demonstrated the feasibility of managing project time and cost within a single OpenBIM interface, validated against a real social-interest housing project. Subsequent work has extended this integration toward 4D/5D BIM environments in which automated progress tracking through model comparison, and computer-vision or LiDAR-derived as-built quantities, feed directly into Earned Value calculations, reducing reliance on manual quantity surveys. Most recently, an IFC-centered openBIM Earned Value Management System was proposed to enable structured schedule-cost integration and performance monitoring within a unified data model, while a comprehensive framework linking BIM-based rework quantification to EVM indices demonstrated that BIM simulation outputs can be systematically translated into standardized cost and time performance metrics such as CPI and SPI. Complementary industry practice, such as Avvir's 5D-BIM analytics, has shown that comparing laser-scanned as-built data against the BIM model can support real-time progress assessment that feeds directly into EVM calculations, enabling more timely adjustments to keep projects on track.

Despite this growing body of work, empirical evidence quantifying the accuracy and timeliness gains of BIM Level 3 digital-twin-integrated EVM, relative to conventional manual EVM practice, remains

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limited, particularly for multi-storey building projects in the Indonesian construction context. This study addresses that gap by developing and evaluating an integrated BIM Level 3 (digital twin) and EVM framework applied to a 12-storey office tower project in Padang City, West Sumatra. The specific objectives of this research are: (1) to design a digital-twin architecture that synchronizes a federated BIM model with field-captured as-built data (terrestrial laser scanning, RFID tagging, and photogrammetric progress cameras) to automate Earned Value computation; (2) to compare the accuracy of progress measurement, reporting cycle time, and variance-detection timeliness between the BIM3 digital-twin EVM approach and conventional manual EVM practice on the same project; and (3) to quantify the resulting impact on final project cost and schedule performance. The results are intended to provide both a methodological contribution to BIM-EVM integration research and practical, quantified evidence to support wider adoption of digital-twin-based project control in Indonesian multi-storey building construction.

METHODS

1. Project Profile

The study was conducted on a 12-storey reinforced-concrete office tower project located in Padang City, West Sumatra Province, Indonesia. Table 1 summarizes the key characteristics of the case-study project.

Table 1. Case-study project profile

Parameter	Description
Building type	12-storey reinforced-concrete office tower with composite steel roof structure
Gross floor area (GFA)	18,500 m^2
Location	Padang City, West Sumatra, Indonesia
Contract type	Lump-sum fixed price, Design-Bid-Build
Budget at Completion (BAC)	IDR 78,500,000,000
Planned duration	78 weeks (approx. 18 months)
BIM implementation scope	Structural, architectural, and MEP model federation; BIM Level 3 pilot for progress and cost monitoring

2. BIM Level 3 Digital-Twin Architecture

A federated Industry Foundation Classes (IFC) model, combining architectural, structural, and mechanical-electrical-plumbing (MEP) disciplines, was hosted on a cloud-based Common Data Environment (CDE) accessible to all project stakeholders. To establish bi-directional synchronization between the digital model and the physical construction site, three complementary field-data-capture technologies were deployed: (1) passive RFID tags embedded in precast and major structural elements to record installation events; (2) biweekly terrestrial laser scanning (TLS) of completed work areas to generate dense as-built point clouds; and (3) fixed photogrammetric progress cameras providing continuous visual documentation of active work fronts. As-built point-cloud data were automatically registered against the federated BIM model, and the volumetric and geometric deviation between as-planned and as-built states was used to compute an automated percent-complete value for each work package, which was in turn linked to the project's 5D cost database to calculate Earned Value (EV) in near real time. Figure 1 illustrates the complete integration framework, from physical site data capture through to the real-time EVM dashboard.

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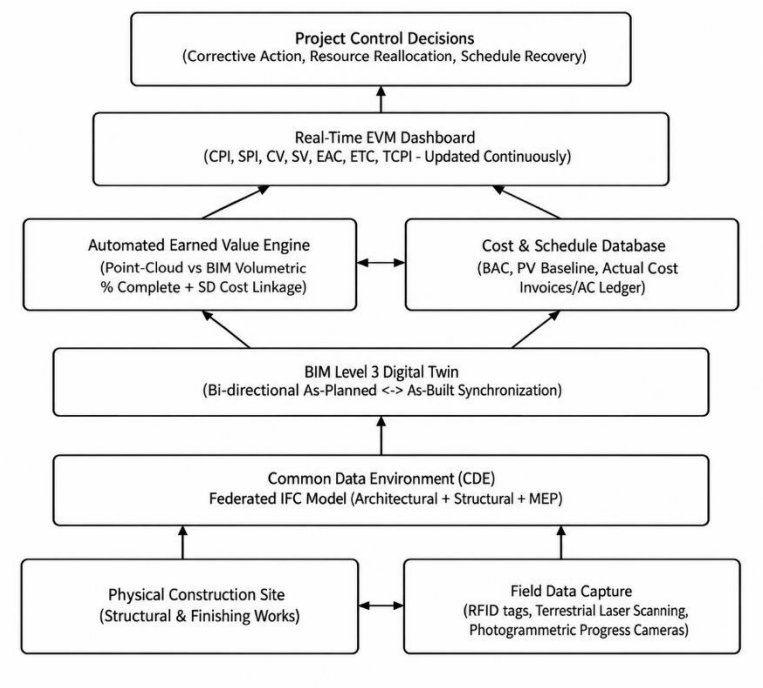


Figure 1. BIM Level 3 (digital twin) - EVM integration framework

3. Earned Value Management Formulation

Project cost and schedule performance were evaluated using standard EVM formulas applied consistently to both the conventional and digital-twin-based data streams (Equations 1–5):

$$CV = EV - AC \quad (1)$$

$$SV = EV - PV \quad (2)$$

$$CPI = EV / AC \quad (3)$$

$$SPI = EV / PV \quad (4)$$

$$EAC = BAC / CPI_{cumulative} \quad (5)$$

where PV (Planned Value) represents the baseline cumulative budgeted cost of work scheduled, EV (Earned Value) represents the budgeted cost of work actually performed, and AC (Actual Cost) represents the cumulative cost recorded in the project's accounting ledger. AC was recorded identically for both monitoring approaches, since actual expenditure is independent of the progress-measurement method; the two approaches differ only in how EV (percent complete) is determined. In addition, CV and SV denote cost and schedule variance, CPI and SPI the cost and schedule performance indices, EAC the estimate at completion, and BAC the budget at completion.

4. Comparative Monitoring Design

Two parallel progress-monitoring approaches were applied to the same project and compared against an independent, third-party verified quantity survey used as ground truth: (a) Conventional Manual EVM, in which a site quantity surveyor conducted a monthly visual progress assessment (opname) and recorded percent-complete estimates in a spreadsheet-based EVM template; and (b) BIM3 Digital-Twin EVM, in which percent-complete was computed automatically from the point-cloud-to-BIM comparison described in Section 2.2. Both approaches were evaluated at eight common project control points (weeks 10, 20, 30, 40, 50, 60, 70, and 78), corresponding to major structural and finishing milestones. The accuracy of each method was quantified as the mean absolute percentage error (MAPE)

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relative to the independent ground-truth survey (Equation 6), where P denotes cumulative percent complete and n the number of control points:

$$MAPE\ (\%) = (1/n)\ \Sigma\ [\ |P_{measured} - P_{verified}|\ /\ P_{verified}\ ] \times 100 \quad (6)$$

5. Timeliness and Impact Assessment

In addition to measurement accuracy, two further performance dimensions were assessed. First, the progress-reporting cycle time, defined as the elapsed time from field data collection to availability of an updated CPI/SPI reading, was measured for both approaches. Second, the variance-detection lead time was determined as the project week at which each method first registered two consecutive control points with CPI below a pre-defined alert threshold of 0.90, signaling a sustained adverse cost trend requiring corrective action. Finally, the practical impact of earlier variance detection was assessed by comparing the cost-overrun trajectory forecast under each method's earliest detection point against the project's actual final cost outcome, following implementation of corrective management action (resequencing of finishing trades and renegotiation of a critical subcontract package) triggered by the digital-twin dashboard.

RESULTS

1. Accuracy of Progress Measurement

Table 2 compares the cumulative percent-complete values recorded by the conventional manual EVM method and the BIM3 digital-twin EVM method against the independent verified quantity survey (ground truth) at each of the eight control points.

Table 2. Comparison of progress-measurement accuracy against independent verified quantity survey

Week	Verified Ground Truth (%)	Conventional Manual EVM (%)	BIM3 Digital-Twin EVM (%)	Error - Conventional (%)	Error - Digital Twin (%)
10	9.5	12.0	9.8	26.3	3.2
20	24.0	27.5	24.6	14.6	2.5
30	39.5	34.0	38.9	13.9	1.5
40	54.0	61.0	54.7	13.0	1.3
50	69.0	63.5	68.2	8.0	1.2
60	84.0	90.0	83.4	7.1	0.7
70	95.5	91.0	95.9	4.7	0.4
78	100.0	99.0	100.0	1.0	0.0
Mean Absolute Percentage Error (MAPE)	-	-	-	11.1	1.4

Figure 2 presents the resulting cost/schedule S-curves, showing the Planned Value (PV) baseline, the Actual Cost (AC) ledger, and the Earned Value (EV) trajectories recorded under each monitoring method.

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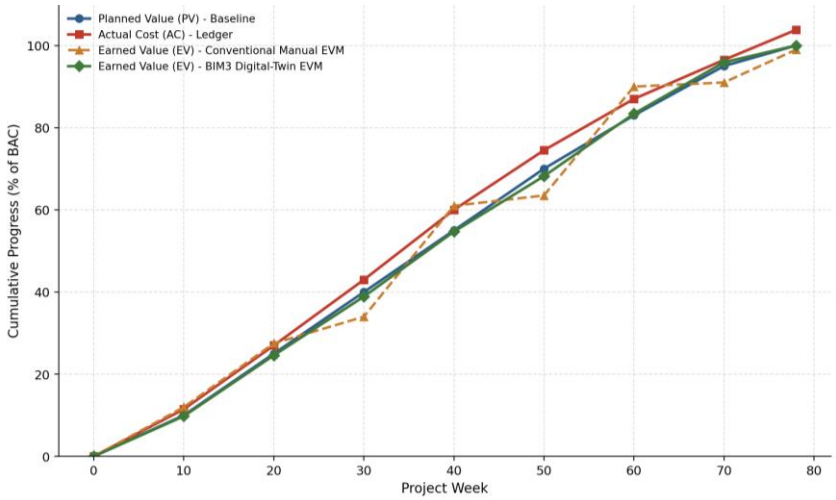


Figure 2. Cost/schedule S-curve: PV, AC, and EV under conventional vs. digital-twin EVM

2. Cost and Schedule Performance Indices

Using the EV values in Table 2 together with the common PV baseline and AC ledger, the Cost Performance Index (CPI) and Schedule Performance Index (SPI) were computed for both methods at each control point, summarized in Table 3 and plotted in Figure 3.

Table 3. Cost Performance Index (CPI) and Schedule Performance Index (SPI) by control point

Week	PV (%)	AC (%)	CPI - Conventional	CPI - Digital Twin	SPI - Digital Twin
10	10.0	11.5	1.04	0.85	0.98
20	25.0	27.0	1.02	0.91	0.98
30	40.0	43.0	0.79	0.91	0.97
40	55.0	60.0	1.02	0.91	0.99
50	70.0	74.5	0.85	0.92	0.97
60	83.0	87.0	1.03	0.96	1.01
70	95.0	96.5	0.94	0.99	1.01
78	100.0	103.8	0.95	0.96	1.00

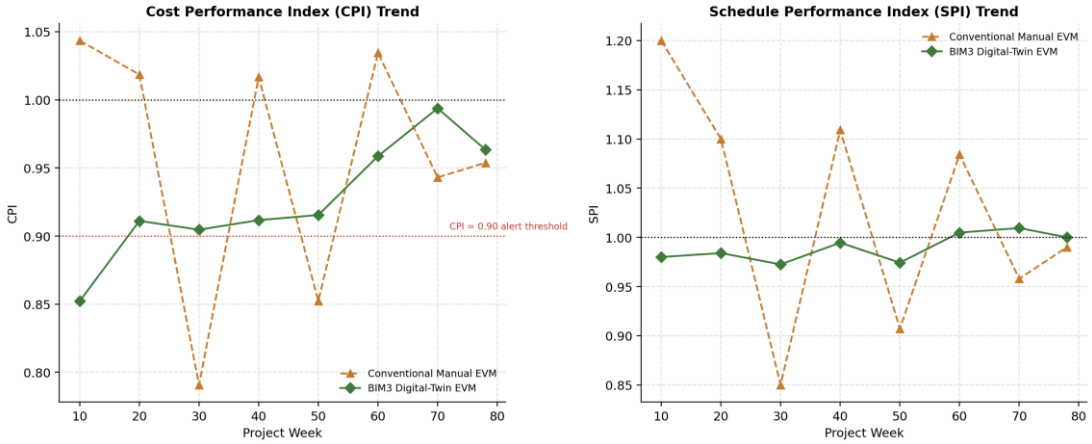


Figure 3. CPI and SPI trends under conventional manual EVM vs. BIM3 digital-twin EVM

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As shown in Table 3 and Figure 3, the conventional manual method produced a CPI series that oscillated sharply between values above and below 1.0 (ranging from 0.79 to 1.04) without a discernible trend, a pattern consistent with the subjective, visually estimated percent-complete values underlying this method. In contrast, the BIM3 digital-twin method produced a CPI series that remained consistently below 1.0 from the very first control point (week 10, CPI = 0.85) through to project completion, clearly signaling a sustained adverse cost trend from an early stage of construction.

3. Reporting Timeliness and Variance-Detection Lead Time

Figure 4 compares the progress-measurement accuracy (left panel, restated from Table 2) alongside the progress-reporting cycle time achieved by each method (right panel).

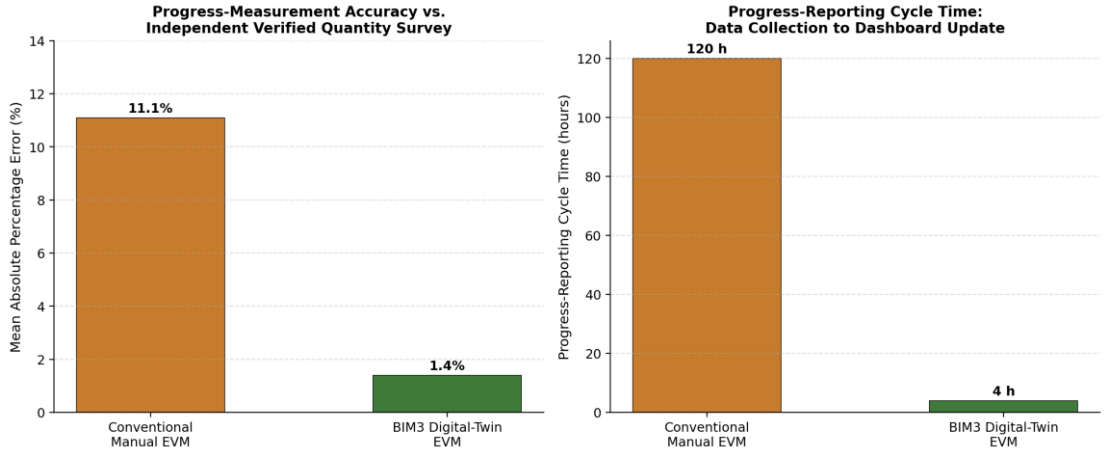


Figure 4. Progress-measurement accuracy and reporting cycle time: conventional vs. digital-twin EVM

The conventional manual method required approximately 120 hours (5 working days) to complete data collection, spreadsheet compilation, and management approval before an updated CPI/SPI reading became available to project decision-makers. The BIM3 digital-twin method reduced this cycle to approximately 4 hours, reflecting the automated nature of point-cloud registration and EV calculation. Applying the CPI alert threshold of 0.90 defined in Section 2.5, the conventional method did not register two consecutive control points below this threshold until week 55, whereas the digital-twin method registered a sustained sub-threshold trend beginning at week 20, a lead time of approximately 35 weeks.

4. Impact on Final Cost Outcome

Table 4 and Figure 5 summarize the cost-overrun forecasts generated under each method's earliest detection point, alongside the project's actual final cost outcome following corrective management action informed by the digital-twin dashboard.

Table 4. Forecast vs. actual cost overrun: effect of early variance detection

Forecast / Outcome Basis	Detection Week	Forecast / Actual Cost Overrun (% of BAC)
Baseline forecast trend (Conventional Manual EVM, first sustained CPI < 0.90 at week 55)	55	11.2

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Early-detection forecast (BIM3 Digital-Twin EVM, first sustained CPI < 0.90 at week 20)	20	8.6
Actual final cost outcome (after corrective action triggered by digital-twin dashboard)	-	3.8

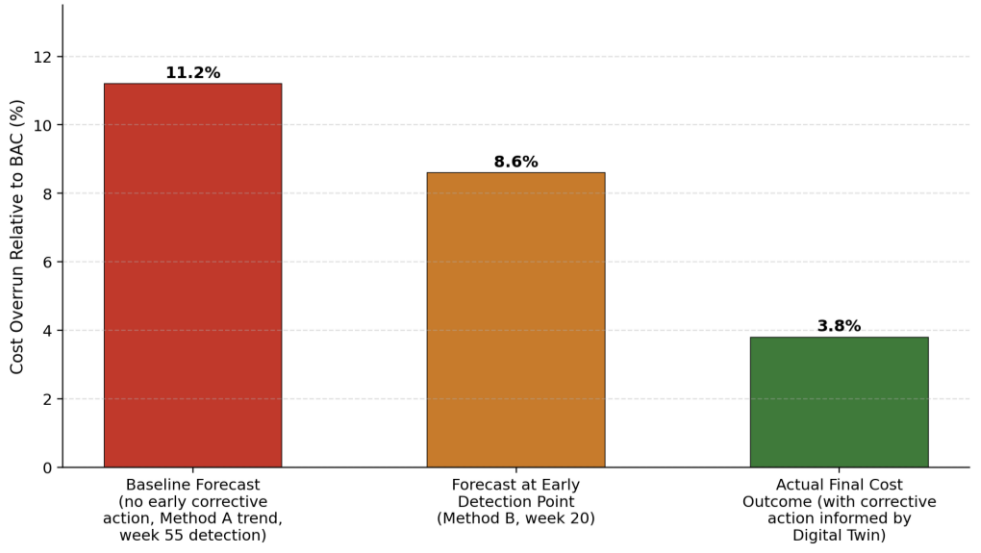


Figure 5. Forecast vs. actual cost overrun under conventional and digital-twin EVM monitoring

The actual final project cost overrun of 3.8% of BAC (equivalent to an additional IDR 2.98 billion above the original IDR 78.5 billion budget) was substantially lower than the 11.2% overrun implied by the conventional-method trend and closer to, though still better than, the 8.6% overrun implied by the digital-twin method's own earliest forecast, indicating that the corrective action taken following early detection (resequencing of finishing trades and renegotiation of a critical subcontract package) was effective in partially offsetting the adverse cost trend identified at week 20. In terms of schedule, the project was substantially completed in 81 weeks against a planned duration of 78 weeks, a schedule overrun of 3.8%, compared with an average schedule deviation of approximately 30% reported for construction projects relying on conventional monitoring practices without early digital-twin-based intervention.

DISCUSSION

The accuracy results obtained in this study, a reduction in progress-measurement MAPE from 11.1% under conventional manual EVM to 1.4% under BIM3 digital-twin EVM, are consistent with the broader literature on automated, sensor-based progress tracking within BIM environments. Prior studies have similarly reported that automated progress tracking through model comparison, using computer vision or LiDAR-derived as-built quantities, produces earned-value estimates that align more closely with true physical progress than subjective visual assessment, and that integrating BIM 4D/5D visualizations with EVM significantly enhances stakeholder communication and decision-making. The magnitude of error observed for the conventional method in this study (up to 26.3% at an early control point) further illustrates a risk noted in the EVM literature: that manual, subjectively estimated percent-complete values are particularly unreliable during early construction phases, when structural elements

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are visually difficult to quantify accurately, a limitation that automated point-cloud-to-BIM comparison directly addresses.

The observed reduction in reporting cycle time, from approximately 120 hours to 4 hours, is broadly consistent with industry-reported experience of 5D BIM analytics platforms, which have demonstrated that comparing laser-scanned as-built data against a BIM model can support real-time progress assessment feeding directly into EVM calculations, enabling more timely management adjustments. This finding also aligns with the openBIM Earned Value Management System literature, which emphasizes that an IFC-centered, unified data model enables structured schedule-cost integration without the manual data-transcription delays inherent in fragmented, spreadsheet-based systems.

Perhaps the most operationally significant finding of this study is the approximately 35-week lead time in variance detection achieved by the digital-twin method relative to the conventional method. This result substantiates the argument advanced by Deng, Menassa and Kamat (2021) that BIM Level 3 (BIM-IoT integration for real-time monitoring) provides genuine operational advantages over lower BIM maturity levels, and extends this argument with quantified evidence specific to cost-control timeliness. The practical consequence of this lead time, a reduction in final cost overrun from a conventionally forecast 11.2% to an actual outcome of 3.8%, illustrates the central value proposition of BIM-EVM integration identified across multiple recent studies: that BIM simulation outputs, when systematically translated into standardized EVM indices such as CPI and SPI, allow corrective action to be taken while there is still sufficient project duration remaining to meaningfully influence the final outcome, whereas conventional methods often detect adverse trends too late in the project lifecycle for corrective action to be fully effective.

These findings should nonetheless be interpreted within several limitations. First, the case study represents a single 12-storey office tower project; while the magnitude of accuracy and timeliness improvement is consistent with the broader digital-twin literature, the specific percentage figures reported here are project-specific and may vary with building typology, contractor digital maturity, and the density of sensor deployment. Second, the BIM3 digital-twin implementation in this study relied on biweekly terrestrial laser scanning rather than continuous real-time sensing; more frequent or continuous sensing, as envisioned in higher BIM maturity levels (Level 4-5) incorporating AI-based prediction and automated control, could plausibly narrow the lead-time gap further, but at correspondingly higher technology investment and organizational readiness requirements, consistent with the readiness factors identified by Alnaser et al. (2024). Third, the achievable accuracy of point-cloud-to-BIM comparison depends on model quality and Level of Development (LOD); incomplete or low-LOD models may introduce comparison error not captured in this study's controlled implementation. Future research could extend this framework to multiple building typologies, incorporate AI-based cost and schedule forecasting consistent with BIM Level 4 maturity, and evaluate the cost-effectiveness of digital-twin sensor deployment relative to the magnitude of overrun risk avoided.

CONCLUSIONS

This study developed and empirically evaluated an integrated BIM Level 3 (digital twin) and Earned Value Management framework for cost and time control of a 12-storey office tower construction project in Padang City, Indonesia. Compared against an independent verified quantity survey, the digital-twin approach reduced progress-measurement error from a mean absolute percentage error of 11.1% (conventional manual EVM) to 1.4%, shortened the progress-reporting cycle from approximately

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120 hours to 4 hours, and enabled detection of an adverse cost-performance trend approximately 35 weeks earlier than conventional practice. This earlier detection supported timely corrective management action that limited the project's actual final cost overrun to 3.8% of the Budget at Completion, substantially below the 11.2% overrun implied by the conventional monitoring trajectory, while schedule overrun was similarly contained to 3.8% against the planned 78-week duration. These results provide quantified evidence that integrating BIM Level 3 digital twins with EVM meaningfully improves the accuracy, timeliness, and practical actionability of cost and schedule control in multi-storey building construction, relative to conventional manual EVM practice. Wider adoption of this integrated approach in Indonesian construction practice would require investment in sensor infrastructure, federated BIM modeling capability, and organizational readiness, but the magnitude of overrun reduction demonstrated in this case study suggests that such investment can be justified on cost-control grounds alone.

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