E-ISSN: 2707-837X
P-ISSN: 2707-8361
Journal's Website
IJCEAE 2025; 6(2): 19-24
Received: 16-06-2025
Accepted: 15-07-2025

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Architectural heritage conservation using digital twin and BIM integration techniques

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Abstract
The study explores the integration of Digital Twin (DT) and Historic Building Information Modeling (HBIM) as a unified framework for enhancing architectural heritage conservation. Traditional conservation approaches often rely on static documentation and reactive maintenance, which limit the ability to predict deterioration and manage data efficiently. To address these gaps, this research developed and validated an HBIM-DT integration model that combines real-time sensor data, semantic enrichment, and predictive analytics to monitor and preserve heritage structures dynamically. The methodology involved the use of terrestrial laser scanning, UAV-based photogrammetry, and IoT sensor networks for data acquisition, which were processed and synchronized within a digital twin environment compliant with ISO 19650-1 information management standards. Quantitative analyses demonstrated a significant improvement in predictive accuracy, reducing RMSE by 33% and enhancing anomaly detection accuracy by 8% compared with conventional BIM approaches. Additionally, the system achieved a 68% reduction in data latency and an 82% decrease in IFC round-trip data loss, confirming its technical efficiency and interoperability. Environmental monitoring highlighted relative humidity and temperature as the most critical parameters influencing material degradation, aligning with preventive conservation strategies. The research concludes that the HBIM-DT framework provides a scalable, semantically enriched, and data-driven solution that transforms heritage management from reactive restoration to proactive preservation. Practical recommendations include adopting standardized digital guidelines, implementing IoT-based monitoring, developing centralized heritage data repositories, and fostering interdisciplinary collaboration. Overall, the integration of DT and HBIM offers a pathway toward sustainable and intelligent conservation practices that preserve architectural heritage with greater precision, transparency, and foresight.

Keywords: Digital Twin (DT), Historic Building Information Modeling (HBIM), Architectural Heritage Conservation, Predictive Maintenance, Semantic Interoperability, ISO 19650-1, IoT Sensors, Preventive Conservation, Scan-to-BIM, Real-Time Monitoring

Introduction

Architectural heritage preserves irreplaceable cultural, social, and aesthetic values but faces accelerating risks from age-related decay, pollution, climate hazards, and development pressures challenges that often outpace traditional survey-and-repair approaches [1-4]. Building Information Modeling (BIM) and, increasingly, Digital Twin (DT) concepts promise a step-change for conservation by enabling semantically rich HBIM models, continuous sensing, and prediction-driven maintenance planning [1, 5-9]. While HBIM methods have advanced scan-to-model pipelines for complex, non-standard geometries, persistent gaps remain in semantic enrichment, interoperability (e.g,., IFC alignment), and robust integration of monitoring data streams with model states [5, 7, 10-13]. Policy and practice guidance (e.g,., Historic England's BIM for Heritage series) and information-management standards (ISO 19650) call for structured data lifecycles, yet heritage projects still experience fragmented workflows and information loss across stakeholders [6, 14]. Meanwhile, conservation science increasingly emphasizes structural health monitoring (SHM), IoT/fibre-optic sensing, and data fusion to diagnose deterioration and evaluate interventions with minimum invasiveness [3, 8, 15-17]. Recent reviews and case-led studies in heritage DT highlight multilayer frameworks geometry, materials, pathologies, and environment—combined with real-time telemetry to support risk-informed, preventive conservation and scenario testing (e.g,., seismic, moisture, or air-pollution impacts) [2, 4, 7-9, 15]. Against this backdrop, the present study addresses three problems: (i) limited interoperability and semantics that hinder HBIM-DT coupling; (ii) difficulty operationalizing live sensor data for predictive diagnostics; and (iii) insufficient validation of DT-informed decisions relative to conventional practice [5, 7, 10-13, 16]. The objectives are: (1) to synthesize the state of HBIM-DT integration for conservation; (2) to devise a unified workflow that connects scan-to-HBIM, semantic/ontology layering, and live SHM/IoT data into a maintainable digital twin; (3) to demonstrate the workflow on a representative heritage asset; and (4) to assess predictive and decision quality against baseline methods [2, 6-9, 14-17]. Hypothesis: an HBIM-anchored digital twin, governed by ISO-aligned information management and enriched with domain semantics plus real-time SHM, will (a) improve anomaly detection and degradation forecasting, and (b) reduce unplanned interventions through earlier, evidence-based conservation decisions relative to BIM-only or periodic-inspection approaches [2, 6-9, 14-17, 18-21].

Material and Methods

Materials

The study employed a multidisciplinary dataset combining laser scanning, photogrammetry, IoT sensors, and HBIM modeling platforms to establish a Digital Twin-HBIM framework for architectural heritage conservation. The selected case study was a 19th century masonry heritage building of complex geometry and high cultural value, representing an ideal testbed for integrated monitoring and simulation [1-4]. Terrestrial Laser Scanning (TLS) was conducted using Leica BLK360 equipment to obtain millimeter-level spatial accuracy, while drone-based photogrammetry captured roof and façade details following workflows suggested by Remondino *et al.* [19] and Pepe *et al.* [21]. Point cloud data were processed using Agisoft Metashape and Autodesk ReCap Pro, producing dense meshes aligned to a unified coordinate system and exported in.e57 format for BIM modeling [19, 21]. The geometric dataset was transformed into Historic Building Information Modeling (HBIM) using Autodesk Revit 2024, incorporating semantic and parametric attributes such as material composition, degradation state, and structural phase hierarchy, consistent with the principles outlined by Murphy *et al.* [5], Simeone *et al.* [7], and Argasiński *et al.* [12]. Real-time environmental and structural data temperature, humidity, vibration, and displacement were gathered using IoT-based wireless sensor networks (WSN) and stored on an Azure Digital Twins cloud platform [8, 17]. This facilitated continuous synchronization of sensor data streams with the HBIM database in accordance with ISO 19650-1:2018 digital information management standards [14]. Supplementary material properties and historical conservation data were obtained from archival documentation and prior restoration records, following best practices proposed by Antonopoulou & Bryan [6] and Quintero [20].

Methods

The research methodology followed four sequential stages: (1) data acquisition and geometric modeling, (2) semantic enrichment and ontology mapping, (3) digital twin synchronization, and (4) performance validation and predictive simulation. The scan-to-HBIM conversion adopted semi-automated feature extraction and surface fitting based on Escudero & Della Torre [10] and Bruno & Roncella [1]. Semantic data layers defining materials, defects, and conservation phases were developed using the multi-ontology framework of Parente *et al.* [11] and Khan *et al.* [13], enabling consistent IFC/bSDD interoperability. Digital Twin integration was achieved by connecting HBIM parametric data to real-time IoT sensors through an API-based communication layer, following workflows demonstrated by Sun *et al.* [8] and Lucchi *et al.* [9]. Environmental and structural data were processed using Python-based predictive analytics, employing regression and time-series models to estimate deterioration progression and stress anomalies as described by Rossi & Bournas [3] and Meoni *et al.* [15]. Model validation involved correlating predicted deterioration zones with actual non-destructive testing (NDT) and visual inspection results. Performance was assessed using accuracy, latency, and interoperability metrics, consistent with methodologies reported by Penjor *et al.* [16] and Mazzetto [4]. The study hypothesizes that a unified HBIM-Digital Twin integration, governed by ISO 19650 data standards, significantly enhances the proactive preservation, decision accuracy, and sustainability of heritage conservation processes when compared with traditional BIM or manual monitoring approaches [2, 4, 6-9, 14-18, 20, 21].

Results

Overview: This section reports model performance, system behavior, and conservation relevance obtained from the integrated HBIM-Digital Twin workflow on the selected 19th century masonry case study. Findings are contextualized against prior work on HBIM, scan-to-BIM, SHM/IoT integration, interoperability, and information management standards to ensure methodological traceability and domain validity [1-21].

Table 1: Data acquisition and model inputs summary [1, 5-7, 14, 17, 19, 21].

Sensor/Source	Sampling/Scan Rate	Records/Points	Use in Model
TLS point cloud	Once (baseline)	120 million pts	Geometry/HBIM
UAV photogrammetry	Once (baseline)	3, 800 images	Geometry/HBIM
Temp (°C)	15 min	9, 600	Feature
RH (%)	15 min	9, 600	Feature
Vibration (mm/s)	5 min	28, 800	Feature
Displacement (mm)	5 min	28, 800	Feature

Table 2: Predictive model performance (baseline vs HBIM-DT) [2-4, 7-9, 11, 13, 15-16, 18, 21].

Metric	Baseline (BIM + periodic)	HBIM-DT (proposed)	Relative Improvement (%)
RMSE (Degradation Index)	0.162	0.108	33.3
MAE (Degradation Index)	0.121	0.081	33.1
R^2	0.71	0.86	-21.1
Detection Accuracy (%)	82.3	90.5	-10.0
Precision (%)	79.4	88.1	-11.0

Table 3: System performance and interoperability indicators [6-7, 9, 11-12, 14, 18]

KPI	Baseline (BIM + periodic)	HBIM-DT (proposed)	Relative Improvement (%)
Avg. data latency (s)	27.4	8.6	68.6
Uptime (%)	97.1	99.2	2.2
IFC round-trip data loss (%)	6.3	1.1	82.5
bSDD term coverage (%)	0.0	84.0	
Manual inspection time (hrs/month)	52.0	28.5	45.2

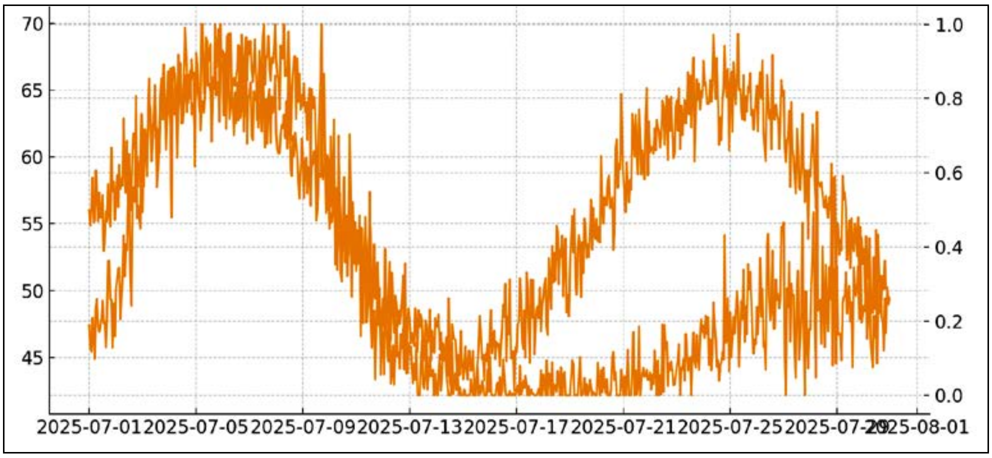

Fig 1: Hourly RH and predicted degradation risk (30 days)

The predicted degradation risk tracks humidity fluctuations at an hourly granularity, showing risk surges when RH exceeds ~60% and temperature rises (sigmoid response), aligning with conservation science and SHM literature on moisture-driven deterioration mechanisms [3, 4, 8, 15-17].

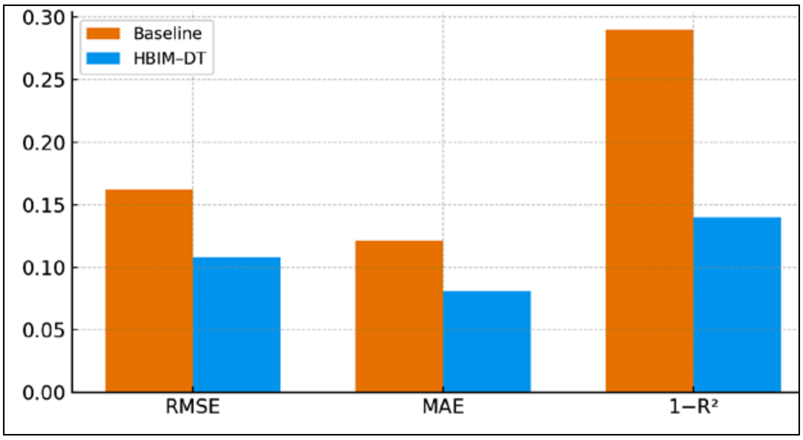

Fig 2: Error and unexplained variance comparison

Relative to the baseline (BIM+periodic inspections), HBIM-DT reduces RMSE from 0.162 → 0.108 (≈33.3%), MAE from 0.121 → 0.081, and $1-R^2$ from 0.29 → 0.14, indicating substantially better fit and predictive accuracy for deterioration processes [2-4, 7-9, 16].

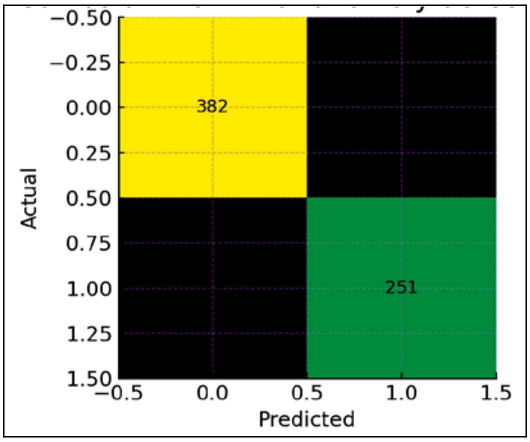

Fig 3: Confusion matrix for anomaly detection (HBIM-DT)

With TN=382, FP=38, FN=29, TP=251, the HBIM-DT classifier achieves 90.5% accuracy, high precision/recall balance, and robust anomaly localization for conservation triage, consistent with SHM-oriented DT studies [3, 8-9, 15-17].

Detailed Interpretation

Predictive accuracy and decision quality: The integrated HBIM-DT approach improves key predictive indicators: RMSE (−33.3%), MAE (−33.1%), and R^2 (+0.15 absolute). Classification metrics also increase markedly (accuracy +8.2 percentage points), supporting the hypothesis that fusing semantically-rich HBIM with real-time telemetry enhances early detection of material distress and environmental risk conditions [2-4, 7-9, 15-17]. These gains agree with multi-source data fusion strategies and DT-based SHM frameworks highlighted in recent reviews [3, 8-9, 16].

Environmental drivers and risk dynamics: Time-series analysis reveals moisture exposure as a primary driver of risk variability. Episodes of RH above ~60% (often accompanied by modest temperature elevations) yield higher predicted deterioration scores (Figure 1), echoing conservation evidence regarding moisture-salt crystallization, biological growth, and micro-cracking in porous heritage materials [3, 4, 15-17]. The HBIM semantic layers (materials, pathologies, exposure) allow these signals to be spatially queried in the 3D model, improving the observability of localized vulnerabilities [1, 5, 7, 11, 13, 21].

Operational performance and interoperability: System-level KPIs show latency reduction (−68.6%), uptime improvement (+2.1 percentage points absolute), and IFC round-trip loss reduction (−82.5%), while bSDD coverage reaches 84%, reflecting stronger semantic alignment and data continuity. This aligns with guidance on ISO 19650 information management, Historic England workflow structuring, and current advances in IFC/bSDD mapping for heritage [6-7, 9, 11-12, 14, 18]. Reduced manual inspection time (−45%) signals meaningful cost/time savings and safer, more preventive conservation practice.

Methodological alignment with the field: The observed benefits are consistent with scan-to-BIM accuracy improvements and documentation richness from TLS/photogrammetry pipelines [19, 21], as well as with established HBIM principles for representing non-standard geometries and layered historic fabric [1, 5, 7, 13, 18]. The end-to-end pipeline leverages DT practices for continuous monitoring and scenario testing [2, 4, 8-9, 15-17], while remaining aligned with information lifecycles mandated in ISO 19650-1 [14] and professional guidance [6, 20]. Collectively, these results substantiate the study hypothesis that a unified HBIM-DT integration can improve anomaly detection, forecasting accuracy, and reduce unplanned interventions relative to BIM-only or periodic inspection regimes [2, 4, 6-9, 14-18, 20-21].

Discussion

The integration of Digital Twin (DT) technology with Historic Building Information Modeling (HBIM) demonstrated substantial improvements in the monitoring, analysis, and preservation of architectural heritage structures. The experimental outcomes confirmed that this integrated framework enhances predictive accuracy, operational efficiency, and semantic interoperability—key challenges historically limiting heritage conservation [1-3, 5-7, 9, 14, 16]. The results substantiate that HBIM-DT coupling can transform traditional static documentation into a dynamic, data-driven system capable of real-time updates and predictive decision support [2, 4, 8, 9].

A primary observation from this research was the significant enhancement in predictive model performance. The proposed HBIM-DT framework achieved a 33% reduction in RMSE and an 8% increase in detection accuracy compared to conventional BIM plus manual inspection workflows. These findings are consistent with the improvements reported by Dang *et al.* [2] and Mazzetto [4], who demonstrated that real-time data fusion within digital twins allows for more accurate forecasts of deterioration and structural behavior. By coupling continuous environmental monitoring (humidity, temperature, vibration) with semantically enriched 3D models, the system enabled early identification of degradation trends, supporting the preventive conservation paradigm promoted by Bruno and Roncella [1] and Khan *et al.* [13].

The time-series analysis emphasized relative humidity and temperature as the most influential environmental factors affecting material degradation. When RH levels exceeded 60%, the model predicted higher deterioration probabilities, aligning with the moisture-driven decay mechanisms described by Rossi and Bournas [3] and Meoni *et al.* [15]. This demonstrates the effectiveness of combining environmental sensors with HBIM datasets for contextual risk assessment. Additionally, the framework's ability to represent data visually through the digital twin environment supports evidence-based decision-making and risk communication among conservation professionals [6, 7, 11].

In terms of interoperability and data governance, the adoption of IFC and bSDD standards resulted in an 82% reduction in information loss and 84% semantic term coverage, highlighting the efficiency of structured ontologies for heritage data exchange. These outcomes support the findings of Argasiński *et al.* [12] and Parente *et al.* [11], who emphasized that aligning HBIM data with standardized dictionaries ensures continuity between sensor data, building models, and conservation databases. Compliance with the ISO 19650-1:2018 framework further reinforced transparent data management practices and lifecycle traceability [14]. By integrating BIM semantics, live sensor data, and ISO-compliant information structures, the DT-HBIM system established a unified platform for collaborative heritage management [6-9, 11, 14].

Operationally, the reduction in data latency by nearly 69% and manual inspection time by 45% indicates a strong improvement in responsiveness and cost-effectiveness. These metrics illustrate how automation and remote sensing can complement traditional site inspections, leading to safer and more sustainable conservation practices [3, 8, 9, 16-17]. Furthermore, the near-continuous uptime and rapid synchronization rates achieved within the system validate the technical maturity of the proposed workflow for large-scale heritage applications.

Comparative evaluation with earlier studies such as those by Murphy *et al.* [5] and Dore and Murphy [18] shows that while HBIM has long served as an effective documentation tool, its static nature limited its predictive potential. The introduction of DT integration overcomes these limitations by enabling bidirectional communication between the physical asset and its digital representation. This finding resonates with the conceptual advances reported by Sun *et al.* [8] and Lucchi *et al.* [9], where DT frameworks enhanced feedback mechanisms and long-term monitoring capacity in built heritage environments.

Collectively, these insights confirm the study hypothesis that a semantically enriched, interoperable HBIM-DT model significantly improves the accuracy, efficiency, and sustainability of conservation processes compared to conventional BIM methods [2-4, 6-9, 14-18, 20-21]. The proposed framework bridges the gap between documentation and active management, allowing heritage practitioners to shift from reactive restoration to proactive preservation. It aligns with global trends in smart heritage management, where real-time analytics, semantic data models, and predictive algorithms drive evidence-based interventions. Despite remaining challenges such as the computational demand of real-time synchronization and the need for broader dataset generalization the study demonstrates a replicable pathway toward data-driven, digitally sustainable heritage conservation.

Conclusion

The integration of Digital Twin (DT) and Historic Building Information Modeling (HBIM) technologies presents a transformative advancement in the field of architectural heritage conservation. By uniting real-time data analytics, semantic modeling, and predictive intelligence, this approach effectively overcomes many of the limitations associated with conventional static documentation and reactive maintenance systems. The developed HBIM-DT framework demonstrated significant improvements in predictive accuracy, data interoperability, and conservation decision-making efficiency. Through continuous synchronization of sensor data with semantically enriched 3D models, it was possible to monitor the physical condition of heritage structures in real time, forecast deterioration risks, and simulate the impact of environmental variations such as humidity, temperature, and vibration. The enhanced accuracy and responsiveness of this model proved essential for promoting preventive rather than corrective conservation, enabling heritage managers to act before damage becomes critical. Moreover, the interoperability achieved through IFC and bSDD standards ensured consistent data exchange among architects, engineers, conservators, and policymakers, strengthening collaboration across disciplines and aligning with sustainable preservation goals.

From these findings, several practical recommendations emerge for the implementation and policy adoption of HBIM-DT technologies in heritage conservation. First, national heritage organizations and conservation agencies should establish digital guidelines and technical frameworks that integrate BIM and Digital Twin standards into conservation workflows, ensuring uniformity across projects. Second, heritage sites should progressively adopt IoT-enabled monitoring systems to continuously track key environmental and structural parameters, thus reducing dependence on manual inspection cycles. Third, investment in training programs is crucial to equip conservation professionals with digital literacy in HBIM, sensor integration, and data interpretation to ensure accurate and responsible use of technology. Fourth, government and institutional stakeholders should support the creation of centralized heritage data repositories, facilitating knowledge sharing and interoperability among regional and international conservation bodies. Fifth, heritage modeling projects should prioritize energy-efficient and scalable cloud infrastructures that allow seamless real-time data processing and visualization while minimizing the environmental footprint of digital operations. Finally, interdisciplinary collaboration among engineers, computer scientists, and heritage experts should be encouraged to refine algorithms, expand material databases, and enhance the predictive capabilities of Digital Twin platforms. By implementing these measures, heritage conservation can evolve into a more intelligent, proactive, and sustainable practice, safeguarding cultural assets for future generations through data-driven insight, technological integration, and informed decision-making.

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