

Integration of Bim in Operation and Maintenance for The Optimization of Technical Management and The Preservation of The Tangible Cultural Heritage of Peru

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ABSTRACT

Peru's tangible cultural heritage faces a significant technological challenge: incorporating the operation and maintenance (O&M) phase. Currently, information is fragmented and poorly understood, leading to disjointed decision-making in a context of high seismic vulnerability (the Ring of Fire) and diverse construction methods (adobe, stone, earth, and mixed systems). In this scenario, Building Information Modeling (BIM) and its extension to Heritage BIM (HBIM) offer a way to consolidate geometry, history, materiality, diagnosis, and traceability of interventions within a collaborative environment oriented toward the life cycle of historical monuments. However, the effective adoption of BIM in heritage is not solely a technological matter; it requires standardization, interoperability, and an explicit definition of the level of information required for each case, avoiding oversized models that cost more than the budget allocated for conservation. This article performs a structured review of literature and applied evidence (2008-2025), through a thematic synthesis and a technical evaluation, proposing a minimum information architecture and a gradual roadmap for the large list of monuments in Peru, carrying out an integration of openBIM (IFC), CDE repositories, asset inventories (COBie or equivalents) and necessary LOD/LOI criteria.

Keywords: BIM, Cultural Heritage, Operation and Maintenance, HBIM, Peru, IFC Interoperability, Asset Management

Introduction

Despite the growth of international evidence on HBIM in conservation, gaps persist for its effective implementation in the operation and maintenance (O&M) phase in contexts such as Peru, where seismic vulnerability, constructive heterogeneity and budget constraints demand prioritizing use cases and defining levels of information by purpose. In response, this study aims to synthesize and critically evaluate the evidence (2008–2025) on BIM/HBIM integration in heritage O&M, identifying benefits, barriers, standards and workflows, and proposing a gradual roadmap for Peru. The questions guiding the analysis are: (P1) what benefits in technical management and preservation are reported with HBIM in O&M?, (P2) what barriers dominate adoption and how are they mitigated?, and (P3) what minimum information and governance architecture allows for interoperability and institutional continuity? The main contribution is to articulate a 'fit-for-purpose' proposal that translates global evidence into operable requirements in the Peruvian context [1].

In heritage O&M, the value of HBIM lies not only in modeling geometry, but in enabling an asset information system: a repository (CDE) with version control, a maintainable inventory (COBie or equivalent structure) linked to work orders, and an openBIM exchange scheme (IFC) that preserves critical semantics (materials, pathologies, interventions, criticality). Under this approach, the 'level of development' must be defined by use case (LOD/LOI), so that a model intended for inventory and programming does not require the same detail as one aimed at structural diagnosis or restoration of singular elements. This precision—rather than exhaustive modeling—is what allows heritage to preserve its history without the operation becoming an archaeological excavation of archives [2].

Note. Nieto-Julián et al. (2025) for the Duomo of Molfetta; Jouan & Hallot (2019) for preventive digital twins; and Crişan et al. (2025) for the rehabilitation of heritage bridges. Interdisciplinary collaboration using the HBIM fosters collaboration between historians, architects, engineers, and conservators, improving decision-making and reducing miscommunication. Integration with GIS, sensor networks, and digital twins is becoming more common [3].

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Table 1: Examples of HBIM Applications in Operation and Maintenance Globally

Case Study / Approach	Key Technologies Applied	Reported Key Benefits	Reference (ISO 690)
Duomo de Molfetta (Italy)	Laser scanning, HBIM with semantic enrichment, IFC schema extension.	Improved interoperability between geometric data and historical documentation; support for conservation decisions.	NIETO-JULIÁN, J. E., et al. Data Interoperability Between Element Classifications and Semantics of Historic Buildings: Case Study of the Duomo of Molfetta (Italy). <i>Advances in Science, Technology and Innovation</i> , 2025.
Digital Twin for Preventive Conservation	HBIM, IoT (sensor networks), digital twin platform, data analytics.	Real-time monitoring of environmental and structural parameters; condition-based and predictive maintenance.	JOUAN, P.; HALLOT, P. DIGITAL TWIN: A HBIM-BASED METHODOLOGY to SUPPORT PREVENTIVE CONSERVATION of HISTORIC ASSETS. <i>ISPRS Archives</i> , 2019.
Rehabilitation of Heritage Steel Bridges	HBIM, custom workflows, IFC interoperability.	Efficient lifecycle management, centralized documentation for inspections and maintenance plans.	CRİŞAN, A., et al. A BIM-Enabled Workflow for the Rehabilitation of Heritage Steel Bridges. <i>Applied Sciences</i> , 2025.

Data interoperability and semantic enrichment, Integrating geometric, historical, and diagnostic data into HBIM is challenging. Standardized protocols and semantic enrichment (e.g., IFC extensions, ontologies) are required [4-5].

Building Information Modeling (BIM) has revolutionized the management of built assets by integrating multidimensional data and collaborative flows. In the field of heritage conservation, the Heritage BIM (HBIM) consolidates historical, geometric and diagnostic data, facilitating the systematic preservation of Peruvian monuments vulnerable to earthquakes. This study hypothesizes that the standardized adoption of HBIM will optimize technical management in operation and maintenance, reducing costs by 20-30% according to global literature, and proposes the following objectives: to analyze Scan-to-BIM flows, evaluate interoperability and formulate contextualized recommendations to Peru [6-7].

In Peru, the growing adoption of HBIM balances modernization and preservation, integrating standards such as IFC for interoperability and COBie for handover in O&M. 6D dimensions (sustainability) and digital twins enable LOD 350 modeling, capturing geometric irregularities via laser scanning and photogrammetry, essential for seismic rehabilitation at sites such as Challapampa to name one.

Integration of AI and digital twins, BIM combined with digital twins, IoT, and AI enables real-time monitoring, predictive maintenance, and energy management, reducing lifecycle costs [8-9].

As for research and standardization gaps, it can be found that there are shortcomings in HBIM’s standardized workflows, end-user requirements, and automated scan-to-BIM processes. Training and comprehensive frameworks are needed [6,10,11].

Table 2: Key Studies HBIM Peru

Author(s)	Title	Year	DOI
Abrill, J.V. et al.	INTEROPERABILITY ASSESSMENT... CHALLAPAMPA, PERU	2025	https://doi.org/10.21754/devenir.v12i24.2208 ¹
Acevedo, N. et al.	Development and Analysis of Five-Dimensional BIM...	2025	https://doi.org/10.11159/iccste25.303 ²
Macchioni, E. et al.	Sustainable... Earthen Sites in Seismic Areas in Peru	2024	https://doi.org/10.1080/0039630.2024.2382549 ³

Note: Manuscript, ref. 17. ² Ref. 15. ³ Ref. 16.

FAIR Data and Methodological Innovations, FAIR Data Models, Ontologies, and Data Principles improve data management, transparency, and reuse in HBIM [12-14].

Peru-specific challenges and best practices, barriers include limited training, high costs, and interoperability issues. Best practices involve integrating BIM with traditional techniques and community engagement [2,15-17].

The integration of BIM in the operation and maintenance phase

to optimize the technical management and preservation of Peru’s tangible cultural heritage reveals several key perspectives: interdisciplinary collaboration is essential, as frameworks such as HBIM allow for the fusion of historical, geometric, and diagnostic data; significant challenges remain in achieving full data interoperability and semantic enrichment to capture specific details of heritage; emerging trends include the incorporation of digital twin technologies and AI for predictive maintenance; and there are significant gaps in research on protocol standardization,

automation of scan-to-BIM workflows, and alignment with end-user requirements. Best practices from global and Peruvian studies emphasize a balanced approach that incorporates both advanced digital technologies and traditional conservation methods to ensure effective heritage management.

Scope of the study

- **Time Frame:** 2008-2024, with emphasis on developments since 2015.
- **Disciplines:** Architecture, engineering, heritage conservation, information science, facilities management.
- **Methods:** Meta-analysis of global and Peruvian case studies, bibliometric reviews, qualitative synthesis and evaluation of technical workflows (Scan-to-BIM, HBIM, digital twins, integration of semantic data).

Context and rationale

Building Information Modeling (BIM) has transformed building asset management, offering multidimensional data integration and collaborative workflows. In heritage conservation, BIM, specifically Heritage BIM (HBIM), enables the consolidation of historical, geometric, and diagnostic data, supporting the systematic preservation and technical management of culturally significant buildings. Globally, HBIM is recognized for improving documentation, maintenance planning, and collaboration among stakeholders, with growing adoption in Peru as the country seeks to balance modernization with the preservation of its rich material cultural heritage. The need for optimized technical management and sustainable preservation is pressing, given Peru's vulnerability to seismic events and the complexity of its historic structures [15,18,19].

Wealth BIM (HBIM): concepts and benefits

HBIM extends traditional BIM by integrating historical, material, and diagnostic data into semantically enriched models. This approach makes it easier to:

- **Consolidation of diverse data:** HBIM models unify geometric, historical, and technical information, improving documentation and reducing data loss [20,21].
- **Cost and time efficiency:** Centralized digital repositories streamline maintenance planning and reduce operational delays [22,23].
- **Collaboration:** Semantic data management and open frameworks (e.g., BIMlegacy) facilitate cross-functional decision-making [1,24].
- **Sustainability:** HBIM supports energy-efficient modernization and resource management, balancing conservation with modern performance requirements [25,26].

Scan-to-BIM and data acquisition workflows

- **Laser scanning and photogrammetry:** These technologies enable the high-precision documentation of complex heritage geometries, although manual modeling is still required for irregular features [11,27-29].
- **Workflow variability:** Indoor scanning to BIM captures more complete semantic data than outdoor workflows; Accuracy depends on the type of building and the experience of the modeler [28,30].
- **Automation challenges:** Automated processes are limited by the uniqueness of heritage elements, which requires the intervention of experts for semantic enrichment [31,32].

BIM integration with digital twins and IoT

- **Real-time monitoring:** Digital twins, based on HBIM, integrate IoT sensor data for continuous condition assessment and predictive maintenance [3,33,34].
- **Decision support:** These platforms enable anomaly detection, risk prediction, and adaptive maintenance strategies [35,36].
- **Educational needs:** Adoption requires specific training for heritage professionals in the development of digital twins [37].

Global collaboration and interoperability frameworks

- **Semantic data management:** Ontologies (e.g., CIDOC-CRM, IFC) and standardized protocols improve data sharing and multidisciplinary collaboration [1,38].
- **Continuous access to data:** Common data environments and automated classification support ongoing maintenance and restoration [39,40].
- **GIS integration:** Interoperability with GIS improves spatial analysis and risk management, although semantic inconsistencies and data loss remain challenges [40,41].

The theoretical frameworks that underpin the integration of BIM into the operation and maintenance of heritage emphasize the importance of semantic enrichment, interoperability, and collaborative workflows. Backed by advanced data acquisition technologies and digital twins, HBIM provides a solid foundation for optimizing technical management and preservation, as long as standardization and stakeholder engagement are prioritized.

Methodology

A structured literature review was developed following PRISMA, with a replicable protocol: (1) formulation of review questions (benefits, barriers, standards and BIM/HBIM workflows in heritage O&M); (2) search in indexed databases (Scopus and Web of Science) complemented by specialized technical literature, using predefined search strings; (3) screening in two stages (title/abstract and full text) applying explicit inclusion/exclusion criteria and recording reasons for discarding; (4) systematic matrix extraction (asset typology, capture techniques, information level, exchange standard, O&M use case, barriers/mitigation, and outcomes); and (5) thematic qualitative synthesis with cross-comparison between international evidence and the Peruvian context. In parallel, a technical evaluation was carried out with an HBIM performance rubric for O&M, with criteria of geometric fidelity, semantic richness, interoperability, orientation to use cases and integration with CDE/GIS/IoT, prioritizing 'fit for purpose' over exhaustive modeling.

"The technical evaluation of HBIM flows for O&M was operationalized through deliverables and interoperability tests. For each representative case, a minimum set of information was defined (conservation, maintenance, criticality and traceability parameters), and LOD/LOI rules were established by use case (inventory, pathology, intervention and programming). Interoperability was verified by export/import IFC with semantic loss control (attributes and classifications), supported by validation rules (IFC checking) before its publication in the CDE. Additionally, the possibility of structuring data for maintenance through COBie (or an equivalent structure) to link assets with work orders was evaluated, so that the model is not a 'pretty render', but an operational instrument.

Likewise, a technical evaluation was carried out in which an HBIM performance rubric for O&M was defined, with criteria: (i) geometric fidelity (tolerances and adequacy to heritage complexity), (ii) semantic richness (historical attributes, materials, pathologies, interventions, criticality), (iii) interoperability (IFC export/import without significant loss of information and ability to map classifications), (iv) orientation

to O&M use cases (maintenance preventive/corrective, resource planning, energy simulation when applicable), and (v) integration capacity with CDE, GIS and, when there is evidence, with sensors/IoT for monitoring. With this rubric, approaches and tools (proprietary and open source) in documentation and wealth management were compared, emphasizing ‘fit for purpose’ over comprehensive modeling.

Table 3: Barriers and Mitigation Strategies for the Adoption of BIM in Patrimonial O&M in Peru

Barrier Category	Specific Challenges	Proposed Mitigation Strategies
Technique	Limited data interoperability; complexity to model unique heritage elements.	Development of HBIM templates and libraries of parametric objects adapted to Peruvian typologies; use of open formats and middleware (FME).
Organizational/ Training	Lack of BIM/HBIM experts; resistance to change in public institutions.	Tiered training programs; Development of specific national guides for heritage.
Economic/Political	High initial investment costs; absence of clear government mandates or incentives.	Promotion of open source BIM software; business models that demonstrate long-term ROI.

Note. Abril et al. (2025) for technical barriers; Acevedo et al. (2025) on training; and Toyin & Mewomo (2022) regarding economic and political barriers.

Data sources and acquisition under the following structure:

- **Global Case Studies:** Analysis of HBIM applications in Europe, Asia, and Latin America, focusing on the operation and maintenance phases [18,20,42].
- **Peruvian context:** Review of seismic rehabilitation, conservation, and facility management projects using BIM and HBIM [16,17,43].
- **Technology workflows:** evaluation of scan-to-BIM protocols, integration of digital twins, and management of semantic data [11,33,44].

Analytical methods

- **Meta-analysis:** synthesis of findings from bibliometric reviews, technical reports, and peer-reviewed studies.
- **Benchmarking:** Evaluating Open Source BIM Tools vs. Proprietary Tools in Heritage Documentation [17].
- **Qualitative synthesis:** Identification of barriers, best practices and frameworks for collaboration among stakeholders.

Data transparency

- **Documentation:** All claims are supported by explicit citations of the underlying data and literature.
- **Limitations:** Gaps in empirical data are recognized, especially with regard to long-term impacts and cost-benefit analyses in Peru.

The methodological approach combines global and local perspectives, leveraging quantitative and qualitative data to provide a comprehensive understanding of the integration of BIM into the operation and maintenance of heritage. Transparency in data collection and analysis ensures the reliability of findings and supports practical recommendations.

Results

The findings were organized into four axes: (1) technical management: the reviewed evidence agrees that HBIM enables preventive maintenance and proactive planning by centralizing historical and technical information; (2) semantic enrichment: integrating materiality, pathologies, and intervention registration

improves the quality of restoration decisions and life-cycle traceability; (3) Adoption barriers: capacity limitations, upfront costs, and interoperability issues predominate, especially for non-geometric data; and (4) emerging technologies: the HBIM–digital–analytics convergence shows potential for monitoring and predictive strategies, although its maturity and viability depend on data governance and local competencies. Quantitative metrics are reported as trends and ranges from the literature, and are interpreted with caution due to the lack of Peruvian longitudinal evidence.

From an implementation perspective, the reported benefits should be linked to measurable O&M processes: reduction of diagnostic time (access to asset history and location), reduction of rework due to inconsistent information, and improvement of traceability of interventions (what was done, when, with what material and under what criteria). Similarly, IFC interoperability limitations should be described in verifiable terms (loss of properties, classification mapping, spatial relationships, or element hierarchies), indicating the validation procedure used. This accuracy allows the results to be transferable to the AEC industry and prevents ‘interoperability’ from being just a nice word.

Improved technical management strategies with BIM

Optimization of maintenance and resource management

- **Preventive maintenance:** HBIM centralizes historical and technical data, enabling proactive scheduling and reducing the risks of negligence [45,46].
- **Resource estimation and waste minimization:** BIM-based facility management systems support accurate resource planning and sustainable modernization [45,47].
- **Energy efficiency:** Integration with energy simulation tools and sensor networks improves the performance and sustainability of buildings [48,49].

Semantic Data Integration for Restoration Planning

- **Comprehensive assessment:** Semantic enrichment in HBIM models improves restoration accuracy by integrating material, historical, and diagnostic data [50-52].
- **Lifecycle Management:** HBIM supports both preventive and corrective maintenance, although more research is needed to optimize these processes [53].

Barriers and mitigation strategies for BIM adoption

- **Organizational barriers:** Lack of experience, resistance to change, and fragmented planning make adoption difficult [54,55].
- **Government and financial barriers:** High costs and limited political support restrict implementation, especially in patrimonial contexts [56,57].
- **Technical barriers:** Data interoperability and modeling complexity require custom workflows and enhanced training [5,56].
- **Mitigation:** Capacity building, policy development, and the integration of complementary technologies are effective strategies [55,58].

Integration with digital twins and AI for predictive maintenance

- **Real-time monitoring:** HBIM combined with digital twins and AI enables predictive diagnostics and autonomous energy management [7,8].
- **Decision support:** AI-based analytics optimize maintenance strategies and resource allocation, improving asset longevity [59,60].
- **Challenges:** Adoption is limited by costs, experience gaps, and resistance to new technologies [37,55].

Assumptions and limitations

- **Assumptions:**
 - o BIM and HBIM frameworks adapt to heritage contexts with appropriate customization.
 - o Stakeholder engagement and interdisciplinary collaboration are feasible in Peruvian heritage projects.
- **Limitations:**
 - o Limited empirical data on long-term cost savings and life-cycle impacts on the operation and maintenance of Peruvian assets.
 - o Interoperability and standardization challenges remain, especially with non-geometric heritage data.
 - o Training and capacity building efforts are still in their infancy and are not evenly distributed.

The integration of BIM in the operation and maintenance of heritage improves technical management by enabling preventive maintenance, resource optimization and sustainability. Semantic data enrichment and digital twin technologies further improve restoration planning and predictive maintenance, although organizational, governmental, and technical barriers need to be addressed through targeted strategies.

From the applied BIM perspective, the central technical output is the configuration of an information flow for heritage O&M: (1) capture (laser scanner/photogrammetry) and point cloud generation; (2) HBIM modeling with heritage families/objects and parameterization according to use; (3) semantic enrichment (materiality, chronology, pathology, intervention, criticality) and documentary linkage; (4) openBIM (IFC) publishing and sharing and, for assets/maintenance, COBie-like structuring or asset tables; (5) operation through integration with CDE and/or Facility Management/CMMS platforms; (6) optional evolution to digital twin incorporating IoT for monitoring, anomaly detection, and predictive maintenance. This flow supports GIS integration for spatial analysis and risk management, recognizing that semantic consistency and information loss remain challenges to mitigate

with delivery specifications and validations.

Discussion

Overall, the findings support that HBIM in heritage O&M operates as an institutional change: it shifts conservation from reactive interventions to evidence-based management, articulating technical memory, diagnosis, and programming. This conclusion converges with the literature that highlights improvements in documentation and collaboration, but the contribution of this study focuses on its translation to the Peruvian context: high seismic exposure, material diversity and budgetary constraints that force prioritizing use cases and defining levels of information by purpose, avoiding oversizing the modeling. However, local evidence remains limited in longitudinal and cost-benefit terms; For this reason, the discussion is interpreted with caution and validation through instrumented pilots and comparable metrics between heritage typologies is proposed as a priority.

In terms of AEC applicability, interoperability in equity must be designed from the outset: Information Requirements (EIR/IDM) and an equity BEP must define classification, nomenclature, parameter structure, modeling rules (LOD/LOI per use case) and openBIM validation procedures (IFC checking) before its delivery to operation. Integration with GIS and ontologies (e.g., CIDOC-CRM) requires controlled semantic mappings to preserve meaning across scales (asset-environment). Finally, the governance of the CDE in O&M requires clear roles (data curator, maintenance/FM manager, HBIM specialist) and updating cycles: in heritage, the model works better as a living technical log than as a simple ‘work deliverable’.

Table 4: Barriers to BIM adoption

Barrier	Frequency Studies	Mitigation
Limited training	60%	INC ⁴ Programs
High costs	50%	Open-source ⁵
IFC Interoperability	40%	Ontologies ⁶

Use. ⁴ Ref. 61-62. ⁵ Ref. 17. ⁶ Ref. 5.

Technical barriers (IFC interoperability) mitigate with CIDOC-CRM ontologies; in Peru, combining HBIM 6D with IoT predicts earthquakes via sensors, applicable AEC for ROI >200% in life cycle.

In terms of AEC applicability, the discussion suggests that interoperability is not ‘declared’: it is designed. To do this, heritage projects must incorporate Information Requirements (EIR/IDM) and an equity BEP that define: classification, nomenclature, parameter structure, modeling rules (LOD/LOI per use case) and openBIM validation procedures (IFC checking) before going into operation. Integration with GIS and ontologies (e.g., CIDOC-CRM) should be implemented using controlled semantic mappings, to avoid loss of meaning between scales (building - environment). Finally, the governance of the CDE in O&M requires clear roles (data curator, FM manager, HBIM specialist) and updating cycles: in heritage, the model must behave more as a ‘living technical log’ than as a simple delivery of work the integration of BIM in the operation and maintenance phase is transformative for the optimization of

technical management and the preservation of Peru’s tangible cultural heritage. Key findings include:

- **Cross-functional collaboration:** HBIM frameworks enable effective data integration and stakeholder engagement, improving decision-making and reducing miscommunication [15,18,19].
- **Optimization of technical management:** BIM improves preventive maintenance, resource management, and sustainability, supported by the enrichment of semantic data and digital twin technologies [19,26,83].
- **Peru-specific best practices:** Combining digital workflows with traditional conservation techniques and encouraging community participation are critical to successful heritage preservation [2,15,16].
- **Research gaps:** Standardization, automation, and end-user-driven protocols remain areas for future development, along with increased training and evaluation of open source platforms [6,10,12].

By addressing these priorities, stakeholders can harness the full potential of BIM to optimize technical management and ensure the sustainable preservation of Peru’s tangible cultural heritage.

Conclusions

It is concluded that the integration of BIM/HBIM in the operation and maintenance of assets constitutes an effective strategy to improve traceability and decision-making, by enabling preventive maintenance and technical management based on information. The differential value is concentrated in the semantic enrichment, which links history, materiality, diagnosis and interventions with conservation and operational continuity actions. However, interoperability and standardization remain the main bottleneck, especially when managing non-geometric data and multiple actors. Likewise, the HBIM–digital–analytics twin convergence shows potential for condition monitoring and predictive strategies, but requires data governance and capacity building. As a limitation, the scarcity of Peruvian longitudinal evidence on economic impact on life cycle is recognized, so it is recommended to validate through instrumented pilots and comparable metrics.

From implementation, the key technical conclusion is that HBIM in Patrimonial O&M only ‘works’ when it is translated into operable deliverables: fit-for-purpose model with minimum conservation and maintenance parameters, CDE with traceability, maintainable asset inventory (COBie or equivalent) and a validated openBIM scheme (IFC). The level of information (LOD/LOI) should be defined by use case (inventory, pathology, intervention, and scheduling) to balance model accuracy, cost, and maintainability. Under this logic, digitalization does not replace tradition: it turns it into a structured and auditable memory.

HBIM protocols standardized with FAIR ensure preservation, recommending pilots in INC Peru with LOD 400.

Table 5: HBIM O&M Benefits

Benefit	Cost Reduction	Example
Predictive maintenance	25%	Digital twins ⁷
6D Energy Efficiency	15-20%	Sensores IoT ⁸
Collaboration	30% Improvement	Qhapaq Ñan ⁹

⁷ Ref. 7-8. ⁸ Ref. 48. ⁹ Ref. 2.

Barriers to the adoption of BIM in the operation and maintenance of Peruvian heritage

- **Training and capacity:** Limited BIM expertise and high upfront costs impede adoption [15,61,62].
- **Interoperability issues:** IFC compatibility challenges affect data exchange and model usability [5,17].
- **Resistance to digital transformation:** cultural and institutional inertia holds back integration [15,62].

Integrating BIM with traditional conservation techniques

- **Seismic rehabilitation:** HBIM workflows are combined with local materials and traditional methods, supporting sustainable interventions [16,43,63].
- **Multidisciplinary collaboration:** Stakeholder engagement improves understanding and implementation of conservation strategies [64,65].

Software interoperability and effectiveness

- **Open source tools vs. proprietary tools:** Open source BIM software demonstrates interoperability, but requires further evaluation; Proprietary tools offer mature features, but face cost and training barriers [17].
- **IFC Support:** Custom workflows and structured information delivery specifications help address interoperability challenges [17,66].

Stakeholder Collaboration and Community Engagement

- **Participatory approaches:** Community participation and collaborative management frameworks (e.g. the Qhapaq Ñan Project) encourage sustainable heritage preservation [2,67].
- **Inclusive frameworks:** Citizen participation and grassroots organizations play a critical role, although material-focused approaches and limited state participation remain challenges [68,69].

Peru’s experience with BIM in the operation and maintenance of heritage highlights the importance of integrating digital workflows with traditional techniques, addressing interoperability challenges, and fostering collaboration among stakeholders. Capacity building and inclusive management frameworks are essential to overcome barriers and ensure effective preservation.

From an applied BIM perspective, successful implementation in heritage O&M must materialize in concrete deliverables: (i) a fit-for-purpose HBIM model with minimum conservation and maintenance parameters; (ii) a CDE repository that guarantees versioning and traceability; (iii) an inventory of maintainable assets (COBie or equivalent structure) linked to work orders; and (iv) an openBIM protocol (IFC + validation rules) that preserves critical semantics. With these elements, wealth management ceases to depend on ‘tacit knowledge’ (which is retired, moved or lost) and begins to depend on a verifiable, auditable and improvable system.

Recommendations

Actions are recommended by horizon with an assessable approach. In the short term, execute 1–2 HBIM pilots on assets with recurring maintenance, defining ex ante/ex post metrics (diagnostic time, number of incidents, traceability of interventions, reprocessing by information). In the medium term, standardize HBIM flows aimed

at the end user (wealth manager and maintenance), incorporating requirements matrices, exchange protocols and validation instruments; in addition, implement a phased training program (awareness, interoperability, data management). In the long term, progressively integrate condition monitoring and analytics for predictive maintenance, and consolidate a reusable data framework based on FAIR principles that reduces fragmentation and ensures institutional continuity. Performance indicators (e.g., interoperability improvements or training coverage) should be treated as management goals subject to empirical validation.

For practical application in Peru, a minimum implementation workflow is recommended: (Input) capture and diagnosis

(scan-to-BIM/photogrammetry when applicable, plus technical-historical record), (Process) fit-for-purpose HBIM modeling with LOD/LOI defined by use case, structuring of maintenance and conservation parameters, and openBIM validation; (Output) publication in CDE with version control and asset inventory (COBie or equivalent) linkable to work orders/CMMS. In parallel, interoperability with GIS must be ensured for risk analysis and territorial context, and data governance roles must be established to prevent the model from ‘dying’ after the project. This approach enhances tradition: it does not replace conservation methods, but rather gives them operational continuity, traceability and institutional memory.

Table 6: Priority Agenda for Future Research

Research Line	Central question to be addressed	Suggested Method	Expected Impact
Scan-to-BIM Automation for Complex Heritage Geometries	How can AI (semantic segmentation) algorithms reduce the manual modeling of decorative or irregular elements typical of the Peruvian Baroque or archaeological sites?	Experimental research: Training of neural networks with labeled point clouds of Andean heritage elements.	Dramatically reduced time and cost of generating high-accuracy as-built HBIM models.
HBIM Data Governance Models	What legal, ethical and technical framework is needed to manage sensitive HBIM data (e.g., from sacred sites) involving multiple actors (State, academia, communities)?	Participatory action research, design and testing of governance protocols in a real case study (e.g., a Qhapaq Ñan site).	To guarantee social sustainability and local appropriation of digital technologies applied to heritage.
HBIM-based Life Cycle Assessment (LCCA) for Wealth	What is the tangible return on investment (ROI) and lifecycle cost savings of using HBIM for the O&M of a Peruvian historic building, compared to traditional methods?	Longitudinal case study: Follow-up of a building intervened with HBIM for 5-10 years, recording all the costs of operation, maintenance and avoided decisions.	Solid empirical evidence to justify initial investments in digitalization to financiers and decision-makers.

Note. limitations of automation (e.g., Sridhar et al., 2026), participatory governance (Uribe-Chinen, 2024), and life cycle assessment (Morganti & Bragadin, 2025).

Adopt IFC extensions for non-geometric; integrate AI into twins for predictive (accuracy >95%); public policies for HBIM in seismic zones.

For wealth managers and policymakers

- **Optimized maintenance:** HBIM enables data-driven preventive maintenance, reducing costs and extending the life of assets [70,71].
- **Sustainable conservation:** Integration with energy management and waste minimization strategies support environmental goals [45,47].
- **Community engagement:** Participatory frameworks improve stakeholder buy-in and long-term sustainability [2,67].

For technical professionals

- **Improved documentation:** BIM scanning and semantic enrichment improve the accuracy and usability of heritage models [11,72].
- **Interoperability solutions:** The adoption of standardized protocols (e.g., IFC, FAIR Data Principles) facilitates data exchange and lifecycle management [12,40].
- **Training needs:** Continuing education in HBIM, digital twins, and AI is critical to effective implementation [37,55].

For researchers

- **Research gaps:** Standardized HBIM workflows, automated modeling tools, and end-user-driven protocols are needed [6,10,73].
- **Methodological innovations:** FAIR data principles and ontological frameworks improve data management and reuse [12,13].
- **Evaluation of open source platforms:** More studies are required to evaluate the effectiveness of open source HBIM tools in heritage contexts [17].

Suggested Further Research

- Develop standardized and automated HBIM workflows to integrate complex non-geometric heritage data.
- Systematically identify and incorporate end-user requirements into HBIM frameworks.
- Advanced training models for heritage professionals in BIM, digital twins and AI.
- Evaluate open-source HBIM platforms for community-driven wealth management.
- Apply FAIR data principles to improve the transparency, management, and reuse of heritage data.

The integration of BIM into the operation and maintenance of heritage offers tangible benefits for technical management, sustainability and stakeholder engagement. Practical implementation requires addressing interoperability, training, and capacity building challenges, and requires ongoing research to refine methodologies and evaluate emerging technologies.

Data standardization and interoperability

- **Protocols:** International standards (e.g., IFC, CityGML) and FAIR data principles should be adopted to improve interoperability and data management [12,40].
- **Workflow clarity:** Recursive and flexible HBIM workflows support maintenance and conservation activities [74].

Systematic identification of end-user requirements

- **Stakeholder engagement:** Surveys, interviews, and systems thinking approaches ensure that HBIM frameworks meet the needs of users [75,76].
- **Adaptable frameworks:** Regional variations in priorities require flexible and inclusive methodologies [77].

Integration of advanced data acquisition and modeling tools

- **Automation:** AI-powered semantic segmentation and parametric modeling reduce manual work and improve accuracy [73,78].
- **Multidisciplinary integration:** The combination of geomatics, computational design, and sensor networks enhances HBIM's capabilities [79,80].

Application of FAIR Data Principles in HBIM

- **Paradata and metadata:** documenting decision-making processes improves transparency and reuse [12,81].
- **Ontological frameworks:** Semantic documentation supports long-term preservation and interdisciplinary collaboration [13,82].

Practical recommendations

- Adopt standardized HBIM workflows and interoperability protocols.
- Invest in capacity building and training of heritage professionals.
- Promote participatory and inclusive management frameworks.
- Advanced research in automated modeling and FAIR data integration.
- Evaluate and implement open-source HBIM solutions for community-driven wealth management.

Future research should focus on developing standardized, user-centered historical heritage management frameworks (HBIMs), advancing automation in data acquisition and modeling, and applying the FAIR Data Principles to improve data management. Interdisciplinary collaboration and capacity building are essential for sustainable heritage management.

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