A New Model for the Digital Preservation and Utilization of Historic Buildings: Optimization of a Scene-Adaptive HBIM and VR Integrated Application Process

He Ma [1], Ichita Shimoda [1], Qi Liu [2], Yining Chen [1,3]

[1] The Heritage Studies faculty, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki, Japan - s2321667@u.tsukuba.ac.jp
[2] School of Architecture, Southeast University, 2 Sipailou, Xuanwu District, Nanjing, China
- 220210171@seu.edu.cn
[3] Polytechnic University of Milan, Piazza Leonardo da Vinci 32, 20133 Milano, Italy - yining.chen@mail.polimi.it

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Abstract

This study proposes a scene-adaptive integration process combining Historic Building Information Modeling (HBIM) and Virtual Reality (VR) for the digital preservation and communication of historic buildings. Addressing limitations in conventional workflows, the methodology emphasizes modular flexibility, semantic structuring, and stakeholder-responsive interaction. It is applied to two contrasting heritage sites—the Former Ota Family Residence in Japan and the Battiferro Watergate Guardhouse in Italy—highlighting the system’s adaptability to varying cultural, material, and technical conditions. Through comparative analysis, the Ota case demonstrated superior balance in modeling efficiency, semantic depth, and immersive engagement, while Battiferro prioritized streamlined technical workflows with less interpretive richness. Evaluation metrics covering data acquisition, integration fidelity, and VR usability validated the proposed framework’s effectiveness in enhancing both scientific documentation and public outreach. The findings confirm that scene-adaptive processes can significantly improve relevance, efficiency, and user resonance in heritage visualization. Future research should expand empirical testing across architectural types and integrate emerging technologies to support wider applicability and long-term sustainability.

1. Introduction

1.1 Background and Digital Preservation Needs

Historic buildings are not only physical artifacts but also symbolic representations of local history and collective memory. Amid the rising threats of natural disasters, urban transformation, and aging infrastructure, the demand for scientific, sustainable, and accessible digital preservation methods has intensified globally.

In response, the integration of Historic Building Information Modeling (HBIM) and Virtual Reality (VR) technologies has emerged as a promising direction in digital heritage workflows. HBIM enables accurate modeling, recording, and management of building geometry, materiality, and restoration history. VR, on the other hand, creates immersive and interactive platforms for cultural dissemination, simulation, and public engagement.

Yet despite their respective strengths, both technologies face limitations when applied independently: HBIM often lacks interactivity and user-centered design, while VR environments frequently rely on static models without rich semantic data. To address these limitations, there is an urgent need to develop integrated processes that bridge scientific documentation with dynamic interaction, and enable context-aware preservation and reuse strategies.

1.2 Gaps in Existing Application Processes

Despite growing interest in integrating HBIM and VR for heritage conservation, most current applications remain fragmented and inflexible. HBIM offers geometric precision and data structuring but lacks intuitive interactivity. VR provides immersive experiences but often sacrifices scientific accuracy or adaptive functionality.

Even in integrated workflows, modeling and visualization are often treated as disjointed phases, leading to rigid, project-specific solutions. Such limitations hinder responsiveness to diverse site conditions, user needs, and evolving technologies.

This study responds by proposing a scene-adaptive approach—one that enables dynamic integration of tools, data, and interactions based on context. Rather than predefined templates, it emphasizes flexible, scalable workflows tailored to real-world conservation scenarios.

1.3 Research Objectives and Contribution

The core objective of this study is to propose, implement, and evaluate a scene-adaptive HBIM+VR integration process designed for the digital preservation and utilization of historic buildings. The process addresses the limitations of current applications by emphasizing adaptability, modularity, and semantic coherence across different project contexts.

This research is structured around three key goals:

1. Process Optimization: Analyze and overcome the limitations of existing HBIM+VR workflows, and design a flexible, modular process architecture that integrates HBIM-based data acquisition and management with VR-based interaction and visualization.
2. Empirical Demonstration: Apply the proposed process to two heritage sites with differing conditions—the Former Ota Family Residence (Japan) and the Battiferro Watergate Guardhouse (Italy)—to demonstrate how the process adapts to diverse conservation goals, data environments, and interpretive needs.
3. Comparative Evaluation: Conduct a structured comparative analysis using criteria such as modeling completeness, processing efficiency, and interaction

usability to assess the performance of the proposed process against conventional methods.

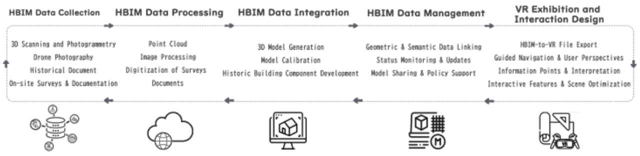

Figure 1. The Application Process of HBIM and VR Technologies Proposed in This Study.

By achieving these objectives, the study aims to offer a practical and generalizable framework for future HBIM+VR applications that require adaptability, accuracy, and immersive communication across varying cultural heritage contexts.

2. Related Work and Theoretical Background

2.1 Developments in HBIM and VR for Heritage Conservation

Over the past decade, Historic Building Information Modeling (HBIM) has emerged as a robust tool for capturing and managing complex spatial and material data associated with heritage structures. Its use of parametric modeling and semantic database systems allows for the precise documentation of geometry, material conditions, and intervention histories. Particularly in restoration planning, HBIM has contributed to lifecycle data management and long-term monitoring strategies .

In parallel, Virtual Reality (VR) has become increasingly important for the interpretation, communication, and engagement of heritage content. Unlike static visualizations, VR environments enable immersive, real-time interaction that can enhance public education, participatory design, and cultural dissemination. Successful examples of VR-based heritage storytelling and experience design illustrate its potential to democratize access to complex historical information.

Integrated use of HBIM and VR began to attract attention as a way to bridge scientific documentation with interactive visualization. Projects such as the reconstruction of Taiwanese heritage academies and European Gothic cathedrals exemplify the power of HBIM for data accuracy and VR for user immersion. However, most of these integrations have been project-specific and lacked scalable or adaptable process frameworks.

2.2 Limitations of Current Integrated Application Processes

Despite technological advancements, current HBIM+VR integrations face several persistent challenges.

Firstly, they often adopt rigid, predefined workflows that are tailored to specific architectural typologies or conservation objectives. Such rigidity reduces adaptability and reusability across diverse heritage contexts.
Secondly, the division between HBIM’s semantic structure and VR’s visualization layer frequently leads to disjointed user experiences and inefficient data flow .

Third, many projects rely on manual data transformation between platforms, increasing the risk of data inconsistency and reducing processing efficiency. Furthermore, interaction design within VR modules is typically generic and lacks adaptive behaviors, limiting its effectiveness in conveying complex cultural narratives or procedural knowledge.

In summary, existing integrated workflows lack a standardized, modular, and context-sensitive architecture, making them unsuitable for broader application in heterogeneous heritage conservation scenarios. These limitations necessitate the development of a framework that supports dynamic adjustments at various stages—data acquisition, semantic modeling, and interaction design—based on scene-specific demands.

3. Proposed Methodology: The Scene-Adaptive HBIM+VR Process

3.1 Review and Evaluation of Integrated HBIM and VR Applications in Heritage Projects

To contextualize the proposed methodology, this section examines three HBIM+VR applications: Huangxi Academy (Taiwan), Shenyang WWII sites (China), and Maizuru Naval Depot (Japan).

These cases reflect distinct priorities: Huangxi emphasized semantic modeling and immersive, time-based restoration planning; Shenyang prioritized educational VR under resource limits via lightweight BIM and historical effects; Maizuru focused on precise geometry, integrating point clouds with BIM, though its VR lacked interactivity.

From these examples, three key advantages of HBIM+VR integration emerge:

1. Preservation Support: Structured HBIM enhances restoration with precise data, ontology-driven queries, and spatial analytics—vital for complex repairs and cross-disciplinary validation.
2. Cultural Dissemination: Immersive VR offers emotional, experiential access to heritage through multimodal storytelling and spatial interaction, promoting engagement across diverse audiences.
3. Cross-Disciplinary Adaptability: Integrated platforms support collaboration via cloud sharing, time-series model management, and interactive queries, expanding both interpretive and academic utility.

Case	Data Capture	Integration	VR Use	Focus
Huangxi Academy	Laser + photo; high detail	Ontology-based model; cloud-linked	Semantic VR + timeline	Research & restoration
WWII Sites in Shenyang	Manual survey + archives	Basic annotation; low complexity	Story-driven VR; visual effects	Public education
Maizuru Warehouse	Laser + photo; material detail	Static attributes; no updates	Basic VR tour; low interaction	Damage mapping

Table 1. Comparison of HBIM+VR Integration Across Three Heritage Case Studies

Together, these cases show how HBIM+VR can be adapted across contexts—offering both technical rigor and communicative power essential for sustainable heritage conservation.

3.2 Scene-Adaptive Principles and Strategic Framework

In the context of historic building preservation, scene adaptability refers to the capacity of a digital workflow to dynamically adjust its technical modules and procedural

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strategies according to contextual conditions—such as building typology, environmental risk, project goals, resource constraints, and stakeholder needs. Rather than serving as a fixed pipeline, the proposed HBIM+VR integration operates as a flexible decision-making architecture that evaluates scene-specific inputs and activates appropriate processes.

This adaptability functions as a meta-framework that governs how individual modules—data acquisition, semantic modeling, or VR interaction—are selectively customized or excluded. For instance, rural wooden buildings with limited data and strong public outreach goals may prioritize lightweight scanning and narrative VR. In contrast, complex urban heritage may demand high-precision semantic modeling and time-based simulations for expert users.

Three guiding principles structure the adaptive strategy:

1. Modular Flexibility: Each technical module—whether in data capture, modeling, or VR design—is loosely coupled and customizable. Modules can be selected, reordered, or excluded depending on scene complexity and project needs.
2. Scene-Specific Optimization: The methodology maps each stage of the process to situational factors such as material properties, architectural style, environmental risks, and intended use (e.g., academic analysis, museum display, public education).
3. Stakeholder-Oriented Design: The process actively incorporates user profiling (researchers, restorers, tourists) to inform interaction models and visualization priorities. Tools and outputs are tuned to different literacy levels, cognitive goals, and usability expectations.

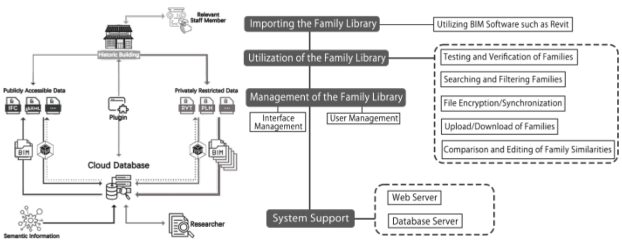

Figure 3. Modular Workflow Architecture for HBIM Family Library Management and Usage

The strategic framework developed from these principles takes the form of a flow-based architecture. At its core lies a decision-making layer that evaluates contextual inputs and selects suitable processing paths. This framework enables project teams to retain control over data quality and interaction expressiveness while reducing redundancy, overengineering, or misalignment across project stages.

3.3 Data Collection and Processing Strategies

3.3.1 Selection Logic for Multi-Source Data Acquisition

In scene-adaptive workflow, data acquisition methods must align with scene-specific variables such as building scale, structural material, accessibility, and conservation intent. Rather than enforcing a uniform technique, the process emphasizes fit-for-purpose combinations based on contextual demands.

For small rural timber buildings with limited access, handheld measurement or mobile scanning offers low-cost feasibility. These methods prioritize community-driven use and fast modeling over absolute precision. In contrast, monumental stone structures may require terrestrial laser scanning (TLS) paired with UAV photogrammetry to ensure geometric completeness and high-resolution surface capture.

Projects in intermediate conditions—such as mid-scale civic heritage—can adopt hybrid approaches. Rangefinders, DSLR photogrammetry, and selective archival integration together provide a balanced dataset suitable for general documentation and narrative VR.

Additionally, where prior records exist (e.g., architectural drawings, repair logs), they can complement modern scans to construct layered historical models. The logic lies in adjusting data types, scale, and resolution to best reflect the heritage context and intended downstream use.

This approach avoids overengineering or underrepresenting critical features. By embedding selection within scene logic, the process enables technical efficiency and heritage relevance simultaneously—core tenets of context adaptability.

3.3.2 Data Cleaning and Preprocessing Mechanisms

Preprocessing transforms raw spatial and visual data into structured, interoperable formats. In scene-adaptive model, this step is responsive to both input condition and modeling intention—ranging from lightweight interpretive models to high-detail restoration datasets.

For basic surveys with manual inputs, cleanup involves redrawing inconsistent linework, inferring missing geometry, and aligning data with historical references. In high-resolution workflows, especially those using TLS and photogrammetry, processes such as point cloud denoising, mesh fusion, and texture correction are essential to ensure consistency across sources.

Mid-level projects often rely on semi-automatic routines: bounding box alignment, geometric simplification, or color balance adjustments. These workflows aim for efficient usability while retaining key architectural cues for visualization or planning tasks.

Crucially, preprocessing in complex scenes may also involve semantic tagging and time-layer classification—especially when archival material is integrated. This supports the creation of dynamic, layered models for evolving heritage interpretation.

In all cases, preprocessing is not a fixed pipeline but an adaptive mechanism tuned to data quality, project goals, and scene constraints. It ensures that the HBIM+VR foundation remains accurate, coherent, and purpose-fit.

3.4 Information Integration and Model Management

3.4.1 Semantic Modeling and Time-Series Data Structuring

In the scene-adaptive HBIM process, semantic modeling is not a fixed technical routine but a flexible logic framework that responds to situational needs and project priorities. Whether the goal is archival documentation, public education, or technical simulation, the process begins by identifying the appropriate semantic granularity—ranging from basic geometric features to nuanced historical metadata. A unified yet extendable family template structure is recommended, enabling modular inclusion of attributes such as geometry, materials, damage types, repair chronology, and construction techniques.

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The depth of modeling is directly influenced by resource constraints, expected output fidelity, and the temporal or disciplinary scope of the project. In scenarios with limited data or funding, simplified templates focus on core structural geometry and key material categories. In contrast, complex cases may demand timeline-based modeling, embedding multi-stage deterioration records and component-level restoration histories to support predictive maintenance and policy planning.

This process-driven flexibility ensures that each semantic modeling step—ontology design, metadata binding, component hierarchy definition—is executed not by convention but through deliberate, context-specific decisions. By aligning modeling resolution with actual use-case demands, the HBIM model transforms into a responsive digital infrastructure, enhancing usability across domains such as heritage conservation, academic analysis, and participatory cultural engagement.

3.4.2 Multi-Level Data Management and User-Oriented Optimization

In the scene-adaptive workflows, data management is not merely a backend operation but a strategically tuned mechanism shaped by collaborative scale, data volatility, and contextual constraints. Rather than adhering to a singular static architecture, the system must accommodate a spectrum of scenarios—ranging from offline single-user projects to multi-stakeholder, cross-institutional collaborations—by structuring its logic around modular and scalable components.

For solo or low-collaboration environments, local databases with unified access control provide a cost-effective, stable, and secure means of data preservation. In contrast, projects requiring team-based workflows benefit from cloud-based coordination systems, enabling real-time synchronization, granular permission control, and dynamic version tracking. Furthermore, when long-term reuse, interoperability, or future-proofing is a priority, adopting open standards such as IFC and supporting hybrid access protocols becomes essential for institutional continuity.

The degree of contextual variability also informs interface design, data querying efficiency, and system responsiveness. Management frameworks must therefore support conditional automation—such as scheduled backups, update logging, and role-specific data views—so that the data environment remains adaptable, transparent, and robust. Ultimately, these mechanisms allow the data layer to mirror the flexibility of the modeling logic, ensuring the entire HBIM+VR pipeline remains both operationally efficient and structurally resilient under shifting project conditions.

3.5 VR Exhibition and Interaction Design

3.5.1 Interaction Strategies Based on User Adaptability

In the scene-adaptive HBIM+VR framework, interaction and display design is no longer a fixed outcome but a flexible, scenario-driven process shaped by usage intent, user demographics, and technological limitations. Instead of one-size-fits-all approaches, adaptive interaction strategies are selectively assembled in response to contextual conditions—ranging from public dissemination and academic analysis to restoration support.

This flexibility ensures that immersive design strategies are tailored to situational demands. For instance, public outreach initiatives emphasize narrative engagement, requiring high-immersion environments powered by photorealistic rendering and intuitive multi-modal interfaces. In contrast, restoration-oriented applications prioritize collaborative features, annotation overlays, and temporal visualization of building elements. Academic uses, meanwhile, may demand semantic traceability, timeline navigation, and comparative structure mapping.

These differences are not addressed through isolated tool selection but through procedural logic: complex VR environments for highly detailed HBIM models are generated using high-end game engines and headsets; mid-tier solutions are crafted via modular Unity systems; and budget-sensitive or web-accessible scenarios leverage WebVR, panoramic platforms, or simplified A-Frame implementations. Crucially, interaction mechanisms, semantic overlays, and feedback structures are conditionally assembled to meet identified stakeholder needs and environmental factors.

Figure 4. VR Interaction Interface for Historic Building Visualization Using Unity

Ultimately, this scene-adaptive strategy transforms VR interaction from a visual display into an intelligent response mechanism—embedded with semantic hierarchy, responsive to usability constraints, and guided by situational efficiency. Through this process, HBIM+VR environments transcend visual storytelling, evolving into targeted decision-support, learning, or maintenance systems.

3.5.2 Multi-Modal Display Design and Feedback Mechanisms

The second pillar of scene-adaptive VR implementation lies in the intelligent selection and optimization of hardware and technical pathways. Rather than applying fixed system templates, this approach responds dynamically to variations in data complexity, economic constraints, and deployment goals—aligning each technical configuration to its scenario-specific context.
In projects with high-resolution semantic modeling (e.g., LOD400–LOD500), GPU-intensive configurations are justified by fidelity requirements, often employing Unreal Engine pipelines, HDRP, and real-time simulation tools. These are critical in high-immersion applications such as national museum installations or research-intensive historical reconstructions. By contrast, in lower-complexity or cost-sensitive deployments (e.g., LOD100–200), platforms like WebVR and GLTF-based mobile experiences ensure accessibility without compromising interpretative integrity.
This adaptive reasoning also informs economic calibration: budget-constrained projects benefit from modular open-source toolchains, asset reuse, and browser-based platforms; mid-level budgets deploy hybrid configurations using paid assets, mid-range GPUs, and Unity ecosystems; while high-budget scenarios explore full-spectrum integrations including advanced XR headsets and cross-platform real-time data streams.

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Importantly, this process also integrates hardware-software synergy. Display systems are selected not solely for capability but for compatibility with project-specific needs—such as navigational freedom in educational settings, multi-language support in community engagement, or precision-based annotation in restoration contexts.

Thus, the adaptive logic in hardware and tool deployment not only ensures cost-efficiency and usability but also guarantees that every technical choice is defensible within the goals and limits of each scenario. Through this processual adaptability, the HBIM+VR pipeline becomes a rational, efficient, and robust support system for diverse heritage preservation tasks.

4. Application and Evaluation

4.1 Case Overview: The Former Ota Family Residence

The Former Ota Family Residence, situated within the Japan Open-Air Folk House Museum, is a prototypical example of traditional Japanese wooden architecture. As a well-preserved Edo-period folk house, it offers a rich case for testing the proposed scene-adaptive HBIM+VR integration framework outlined in Section 3.

This structure was selected based on its morphological complexity, historical material authenticity, and socio-cultural relevance as a living heritage asset. Conservation priorities included comprehensive documentation, condition monitoring, and public engagement through immersive interpretation.

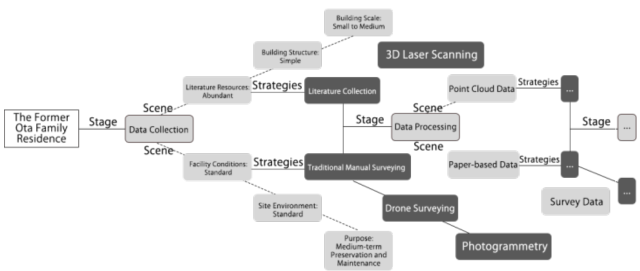

Figure 5. Application of the "Scene-Adaptive Process" in the Former Ota Residence.

To address these priorities, the project required an adaptive workflow capable of responding to specific on-site constraints such as intricate timber joinery, partial inaccessibility of interior zones, and heterogeneous material conditions. These factors made the Former Ota Residence an ideal candidate for testing the methodological flexibility intended by the proposed scene-adaptive HBIM+VR process.

4.2 Implementation of the Scene-Adaptive Process

4.2.1 Data Collection and HBIM Modeling

The HBIM data process for the Former Ota Residence applied the scene-adaptive strategy reflecting local conditions—moderate scale, simple structure, limited equipment, and partially complete records. The acquisition phase combined aerial photogrammetry (via drone), terrestrial laser scanning, DSLR imagery, and manual measurements to compensate for data gaps, especially in unrecorded areas like rear windows or structural joints. Historical repair reports provided dimensional baselines but required onsite validation. Initial photogrammetry faced issues such as poor coverage and lighting inconsistencies, later resolved by refining camera angles, height alignment, and shooting under diffuse light using high-resolution RAW formats.

In the processing phase, historical documents were manually digitized into 2D CAD drawings, with missing parts completed using field data. Photographs were processed through RealityCapture and Metashape, balancing texture quality and model completeness. Resulting meshes were refined in Blender, and all sources—CAD, point cloud, and images—were integrated to validate geometry and capture structural details.

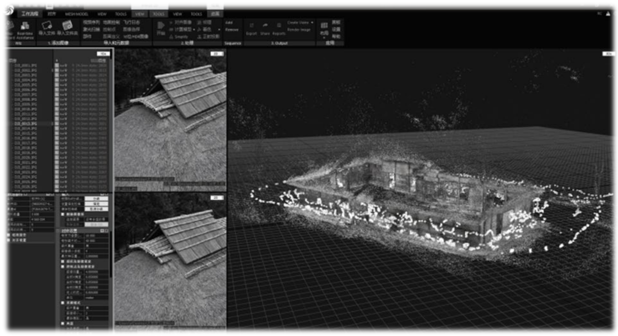

Figure 6. RealityCapture-Based 3D Reconstruction of The Former Ota Family Residence Using Multi-Source Data Integration

This scene-adaptive Process ensured accurate, efficient data modeling under constrained resources, forming a solid base for HBIM model construction and downstream VR applications.

4.2.2 Information Integration and Dynamic Management

The HBIM integration for the Former Ota Residence was pivotal in establishing a context-responsive modeling process. Building on strategies from Chapter 3, multi-source data—including historical records, surveys, and CAD drawings—were unified into a coherent model reflecting the building's cultural and material context. Geometric modeling prioritized non-standard timber elements and traditional joinery; for instance, complex beams were reconstructed in Revit using sweep tools informed by archival slope data and local techniques.

To represent temporal transitions, elements like roofs and beams embedded repair histories, enabling 4D visualization. Material properties, damage records, and spatial logic were structured via parametric definitions, enhancing both accuracy and usability. A hierarchical "Category–Family–Type" library organized components by function, typology, and historical attributes.

For scalability and precision, the system combined PostgreSQL databases with Amazon S3 storage, enabling efficient 3D data handling and real-time access via RESTful APIs. A standardized template harmonized metadata on dimensions, materials, and restoration phases. Python scripts automated IFC mapping, while complex features—such as mortise-tenon joints—were adjusted manually. This scene-adaptive strategy supported efficient modeling, dynamic updates, and long-term heritage preservation.

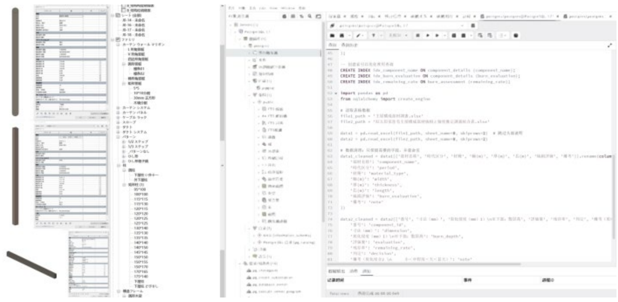

Figure 7. Database-Driven HBIM Structuring with Revit Families and Python-IFC Integration

4.2.3 VR Interaction Design and System Deployment

The VR application for the Former Ota Residence was developed to align with its museum context and diverse visitor needs. Based on user surveys and site characteristics, the system employed a scenario-adaptive interaction strategy emphasizing both cultural interpretation and experiential accessibility.

Interactive modules were structured to reflect situational demands: static panels guided first-time users; dynamic architectural dissection and timeline overlays supported deep exploration; video content conveyed fire history and restoration. These functions were not implemented uniformly, but selected and assembled based on usage scenarios, literacy levels, and hardware capacity.

The development process included model optimization (via Blender and Simplygon), modular scene loading (using Unity Addressables), and lighting strategies suited to indoor/outdoor transitions. Interaction logic combined OpenXR raycasting, prefab-based triggers, and UGUI panels for flexible, multilingual interface delivery. Performance was tuned through LOD control and Meta Quest testing.

This adaptive workflow ensured that the VR system preserved cultural fidelity while maximizing usability and engagement under real-world constraints.

4.3 Comparative Case Analysis and Evaluation

4.3.1 Overview of the Comparative Case and Application Workflow

The Battiferro Watergate Guardhouse in Bologna, Italy—originally built in 1439 and repeatedly restored—is a preserved industrial heritage site repurposed for cultural and educational use.

It was selected for comparison due to similarities with the Former Ota Residence: moderate scale, restoration history, documentation gaps, and public engagement goals. Despite differing types—hydraulic infrastructure vs. vernacular housing—both applied immersive technologies, fitting the scene-adaptive framework.

HBIM development used TLS and drone photogrammetry, with point clouds optimized in ReCap and models created in Revit. Components were semantically tagged for materials and repair phases, supporting historical visualization.

The HBIM model was deployed to Twinmotion for VR, achieving high visual realism with simple animations, though lacking real-time interactivity. Still, it showcased the potential of integrated HBIM-VR for industrial heritage communication.

Overall, Battiferro serves as a baseline case, enabling comparative analysis to assess the adaptability and strengths of the proposed context-aware methodology.

4.3.2 HBIM Process Comparison: Acquisition to Management

The HBIM workflows of the Former Ota Residence and Battiferro Guardhouse illustrate contrasting scene-adaptive strategies tailored to context, goals, and scale. To compare these workflows systematically, this study adopts metrics from (Bruno et al., 2018), focusing on data precision, tool adaptability, acquisition efficiency, and coverage.

At Ota, a post-disaster timber structure with incomplete records, data was captured using drones, laser measurers, and DSLR surveys, emphasizing adaptability and efficiency. Battiferro, a complex industrial site, used TLS and oblique photogrammetry, achieving higher precision but lower operational efficiency. Ota’s approach while Battiferro’s full coverage demanded yielded moderate coverage with optimized resources,disproportionate effort in irrelevant zones.

Processing efficiency further distinguished the two. Ota used Metashape and historical documents for targeted cleanup and semantic enrichment, ensuring integration quality with minimal delay. Battiferro relied on multi-stage filtering in Recap, resulting in longer processing times. Evaluated via data quality, integration speed, and multimodal consistency, Ota showed superiority in balancing fidelity and feasibility.

In data integration, Ota standardized its component libraries based on historical semantics and repair logs, promoting reusability. Battiferro's model lacked structured typologies, limiting management scalability. On data flexibility, semantic depth, and update capability, Ota’s PostgreSQL–S3 hybrid and IFC automation supported real-time changes, whereas Battiferro remained static and file-dependent.

Comparison Item	Ota Residence	Battiferro Guardhouse
Data Capture	Hybrid scanning (drone, DSLR, manual)	TLS + oblique drone imaging
Point Cloud Handling	Optimized cleanup for timber geometry	Dense scan, minor cleanup
Modeling Focus	Timber joinery, repair history	Component hierarchy, phases
Semantic Integration	Integrated material + repair data	Basic metadata only
Data Management	PostgreSQL + S3 with IFC sync	Static Revit model output

Table 2. Comparison of Scene-Adaptive HBIM Workflows between the Former Ota Residence and Battiferro Guardhouse

Thus, using consistent metrics, the Ota workflow demonstrated greater adaptability and resource-conscious effectiveness, aligning with stakeholder expectations and cultural specificity, while Battiferro showcased engineering rigor but limited flexibility.

4.3.3 VR Interaction Comparison: Design and Experience

The VR implementations at the Former Ota Residence and Battiferro Guardhouse differ significantly in terms of interaction design, narrative depth, and technical efficiency. Guided by metrics adapted from Barešytė et al. (2024), this section compares immersiveness, production effort, interactivity, and educational impact.

Ota prioritized narrative realism, embedding time-based reconstructions, texture detail, and immersive transitions. Its VR system included structural disassembly animations, fire restoration playback, and context-sensitive pop-ups. Measured by visual fidelity and historical coherence, Ota achieved high immersive quality. Battiferro emphasized present-state simulation, limiting its visual and emotional depth.

Production-wise, Battiferro scored higher in workflow efficiency, directly importing models with minimal customization. Ota required model simplification, UV baking, and custom scripts, increasing effort but enhancing interpretability. While Battiferro's simulation was output-ready, it lacked interpretive layering.

In user interaction, Ota implemented multi-layered interfaces, offering animations, videos, and interactive nodes for semantic exploration. Battiferro's interaction remained static and function-led, reducing user agency. According to user feedback sampling and engagement metrics, Ota's design promoted intuitive learning and retained attention longer.

On education, Ota's VR conveyed post-disaster recovery and architectural transitions over time, directly supporting museum goals. Battiferro presented engineering functions but omitted deeper cultural narratives. This reduced cognitive engagement and limited the simulation's heritage communication value.

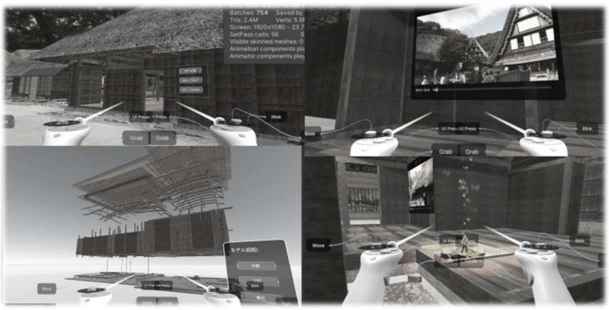

Figure 8. Interactive VR Scenes: Structural Visualization and Narrative Immersion in Heritage Display Platforms in the Former Ota Residence.

In sum, Ota's VR experience scored higher across interpretive, immersive, and pedagogical dimensions, validating the scene-adaptive VR framework's strength in conveying cultural significance.

Comparison Item	Ota Residence	Battiferro Guardhouse
Immersion &Visuals	High realism, historical textures	TLS + oblique drone imaging
Production Strategy	Custom script, texture baking	Direct model use
Interactivity	Animations, pop-ups, video	Simple operation simulation
Educational Content	Disaster recovery time layers	Limited cultural context

Table 3. Comparison of VR Interaction Design and Cultural Engagement in the Two Case Studies

4.3.4 Summary of Comparative Findings and Implications

The comparison highlighted the strengths of the scene-adaptive workflow applied to the Former Ota Residence across all stages. The targeted use of drones, laser scanning, and historical records ensured efficient and purposeful data acquisition. In contrast, the Battiferro project gathered excessive point cloud data, lacking alignment with its research objectives and leading to inefficiencies.

For data integration, the Former Ota Residence adopted a standardized family library with parametric logic, allowing dynamic updates and historical tracking—key for long-term heritage management. Battiferro, relying on static data, lacked this adaptability and semantic depth.

In the VR stage, the Former Ota Residence prioritized immersive storytelling and educational impact. Interactive elements visualized historical transformations and restoration narratives, engaging diverse audiences. Battiferro focused more on structural simulation, offering limited cultural resonance.
However, the Former Ota Residence's approach revealed limitations: reliance on historical texts caused some data gaps, and customized VR features increased production time and cost. Its strong cultural focus also left technical interpretation underdeveloped.

Overall, the Former Ota Residence case demonstrated a balanced yet culturally rich implementation of the adaptive workflow, validating its effectiveness. Still, broader validation across other architectural types is needed to generalize its applicability and refine process efficiency.

5. Discussion and Conclusion

5.1 Summary of Findings and Contributions

This study proposes a scene-adaptive HBIM–VR integration framework that addresses the persistent lack of flexibility, semantic depth, and user-oriented design in conventional digital heritage workflows. Unlike fixed pipelines, the approach emphasizes conditional modularity—enabling tailored configurations based on site typology, data conditions, and interpretive needs. Through empirical application at the Former Ota Residence, the framework demonstrated how selective use of tools (e.g., drone photogrammetry, semantic modeling) and interaction design can align digital outputs with both curatorial intent and user engagement goals. Comparative validation against the Battiferro Guardhouse project further confirmed that technological similarity does not ensure methodological equivalence—context-driven adaptability is essential for relevance and effectiveness. In doing so, this research contributes a transferable process logic that enhances not only technical efficiency but also the narrative and participatory value of digital conservation efforts.

5.2 Limitations and Scope of Applicability

While the proposed scene-adaptive process showed practical value in the HBIM+VR integration for the Former Ota Residence, several limitations constrain its broader applicability. First, its adaptability to future changes remains underexplored. Designed around current project conditions, the workflow has not been tested against emerging variables such as AI-based modeling, IoT-enabled monitoring, or shifting exhibition needs. Long-term flexibility thus requires further validation through process evolution and integration with new technologies.

Second, the empirical scope is limited. Validation was conducted in a specific context—a mid-scale timber structure within a museum environment. Therefore, conclusions may not extend to other typologies, material systems (e.g., masonry or hybrids), or application scenarios like urban sites or archaeological ruins. Broader case evaluations are necessary to test performance under varied conditions.

Third, although the Battiferro Watergate Guardhouse served as a comparative case, the focus was on modeling and exhibition effectiveness rather than workflow adaptability. This narrows the strength of generalization. Diverse case studies with quantitative metrics would better demonstrate scalability.
Lastly, long-term user feedback and operational continuity were not examined. While the proposed process functioned effectively during pilot implementation, its impacts on heritage conservation, visitor engagement, and long-term adaptability remain under-assessed. Closing these gaps is essential for evolving the framework into a robust and transferable methodology for diverse heritage contexts.

5.3 Future Research Directions

Building upon the proposed scene-adaptive HBIM+VR process, future research must further verify its versatility and scalability across broader heritage conditions. While this study focused on a mid-scale wooden building in a museum setting, the applicability of the workflow to other structural types—such as stone or hybrid constructions, urban sites, or ruins—remains untested. Empirical studies should thus encompass varied material systems, scales, environmental contexts, and cultural settings to validate procedural flexibility under diverse project demands.

Technological evolution also prompts methodological expansion. Integrating AI, IoT, and cloud-based platforms could enable real-time synchronization, dynamic data management, and adaptive user experiences. Such updates would allow the process to evolve alongside new computational capabilities, enhancing its long-term relevance.

Additionally, little is known about the framework's performance in sustained implementation. Data-driven evaluations of operational continuity and conservation outcomes over time are crucial to understanding its practical impact. Establishing feedback loops from users and heritage managers would further support iterative refinement.

Finally, practical standardization is necessary for wider adoption. Although adaptability is a strength, current implementation requires high expertise and case-specific configuration. Developing modular toolkits and user-friendly interfaces could reduce entry barriers, making the process accessible to smaller projects and resource-constrained regions.

Advancing these research directions will transform the scene-adaptive process from a tailored framework into a robust methodology for sustainable heritage documentation and dissemination across diverse global settings.

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