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Article

Cyber Representation in Experimental Architectural Restoration: Integrating HBIM, As-Designed BIM, and VR in a Multilevel and Multitemporal Immersive Ecosystem

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Abstract

This study explores the transformative potential of cyber technologies in the preservation, representation, and restoration of architectural heritage. Bridging technical and humanistic dimensions, it examines how tools like Heritage Building Information Modeling (HBIM), As-Designed BIM, and Virtual Reality (VR) support deeper, multilevel, and multitemporal understandings of cultural sites. Central to the research is an experimental restoration project on the castles of Civitella in Val di Chiana (Arezzo), serving as a methodological testbed for a digitally integrated approach. Developed through a scan-to-BIM process, the project yields a high-fidelity immersive ecosystem—both a rigorous model for future restoration and a VR platform enabling access to previously unreachable spaces. Here, representation is not a secondary or illustrative phase but a central, operative component in historical interpretation and architectural design. This approach embraces cyber representation: a digitally mediated, interactive, and evolving form that extends heritage beyond its physical boundaries. The immersive model fosters renewed dialogue between past and present, encouraging critical reflection on material authenticity, spatial transformation, and conservation strategies within a dynamic, participatory, interactive webVR environment. Representation thus becomes a generative and narrative tool, shaping restoration scenarios while enhancing analytical depth and public engagement. The study ultimately proposes a shift in historical storytelling toward a polyphonic, experiential, cyber-mediated narrative—where technology, memory, and perception converge to create new forms of cultural continuity.

Keywords: Virtual Heritage; HBIM (Heritage Building Information Modeling); virtual reality; scan-to-BIM; cultural accessibility; restoration; interactive representation

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1. Introduction

Cultural heritage is a fundamental pillar of collective identity, encompassing both tangible assets, such as monuments, buildings, and artifacts, as well as intangible elements like traditions, practices, and values passed down through generations [1].

In an era where technological advancements continue to transform various disciplines, the methods for preserving, studying, and communicating heritage have also undergone significant evolution. Immersive digital tools—particularly Virtual Reality (VR), Augmented Reality (AR), and game engines (GEs)—are revolutionizing the way users experience, interact with, and interpret historical environments [2]. These technologies offer new possibilities for heritage conservation by allowing users to engage with the past in more dynamic and interactive ways [3]. This shift is particularly significant in the field of architectural heritage, where traditional methods, such as Computer-Aided Design (CAD), often struggle to capture the full complexity of historic structures [4].

The complexity of historic structures arises from their intricate architectural design, construction techniques, and cultural significance, incorporating evolving physical, symbolic, and functional layers. These buildings often feature advanced geometries, like arches and vaults, and materials that respond differently to environmental factors, presenting challenges in their preservation. For instance, Gothic cathedrals with flying buttresses and detailed stone carvings require advanced methods for capturing their full complexity. The preservation of such features requires specialized techniques, as materials like stone and wood deteriorate over time, necessitating precise documentation to assess the changes.

The scale at which these structures are documented is pivotal in capturing their geometric features. Fine-scale measurements are crucial for preserving the minute details, such as ornamental carvings and surface textures, which can be accurately captured using tools like 3D scanning. The sampling distance between measurement points determines the resolution of the data. A smaller sampling distance allows for more precise documentation, ensuring that no details are overlooked, which is vital for restoration efforts. High-resolution methods are particularly valuable in preserving the historical authenticity of structures, as they reveal both the original design and areas that may have deteriorated. The integration of advanced measurement techniques, like laser scanning and photogrammetry, with historical analysis provides a comprehensive approach to documenting cultural heritage. These methods generate accurate digital models that not only preserve the geometric features of buildings but also help in understanding their historical context. This combination of precise data with cultural and historical metadata ensures that the multi-dimensional complexity of historic buildings is retained, allowing future generations to access and understand their significance.

In this context, Historic Building Information Modeling (HBIM) has emerged as a crucial tool to bridge this gap, creating dynamic, data-rich models that blend precise geometry with historical, material, and cultural metadata [5]. By integrating architectural, historical, and cultural information, HBIM supports not only conservation planning but also interdisciplinary analysis and public engagement. It enables a more holistic understanding of the built heritage and facilitates the preservation of its physical and intangible aspects. In parallel, immersive technologies introduce the concept of digital proxemics, a reinterpretation of Hall's (1966) theory of spatial behavior [6], which emphasizes the need to design virtual spaces that are not only spatially accurate but also cognitively coherent and emotionally resonant [7–9]. The integration of immersive technologies into cultural heritage projects fosters a deeper connection between users and the history they explore. Projects such as Inception [10,11], Scan4Reco [12], and CyArk [13] exemplify how these technologies serve as both scientific tools and participatory platforms, democratizing access to heritage sites and enhancing the experience of historical environments.

However, despite the significant potential of HBIM and immersive technologies, several barriers hinder their widespread adoption. Challenges such as high implementation costs, platform incompatibility, and limited digital literacy among heritage professionals have led to slow uptake in many heritage conservation projects. Overcoming these barriers requires the creation of integrated immersive ecosystems—merging HBIM, VR, and narrative strategies—to move beyond static documentation and towards interactive, inclusive experiences that engage diverse audiences in new ways.

This paper presents an integrated and experimental process in which digital representation becomes both a design tool and a narrative device for architectural restoration.

Through the case study of the Castle of Civitella in Val di Chiana (Arezzo, Italy)—a heritage site partially inaccessible due to structural degradation—the study proposes an immersive digital ecosystem that integrates HBIM, as-found and as-designed models, and VR technologies. Developed via a scan-to-BIM-to-VR workflow, the project offers a high-fidelity digital reconstruction that simultaneously documents the historical legacy, reflects the castle's current condition, and envisions a restoration scenario for future generations.

The immersive ecosystem functions not only as a technical support for experimental restoration but also as a virtual museum, accessible through WebVR platforms and standard browsers, broadening participation and inclusivity. By combining accuracy, historical depth, and interactivity, the project reframes the act of restoration as a dynamic and participatory cultural experience. The Castle of Civitella becomes a narrative medium through which digital representation connects past, present, and future—proposing a sustainable, multitemporal, and multilevel approach to heritage conservation.

This methodology demonstrates how immersive technologies can transform restoration into a form of storytelling, preservation, and future-oriented cultural transmission. Crucially, this approach embraces the concept of the cyber representation paradigm in which digital heritage transcends static, two-dimensional documentation to become an interactive, evolving, and relational entity within cyberspace. Cyber representation facilitates a multilayered dialogue between physical and virtual realities, allowing cultural heritage to be experienced not only as a static artifact but as a dynamic and participatory system. It integrates spatial accuracy, historical narratives, and sensory engagement into a cohesive digital presence that evolves, enabling users to navigate multiple temporal and interpretative layers. By embedding restoration projects within this cybernetic framework, digital models become generative platforms for design, education, and community involvement, fostering a deeper, more inclusive connection between people and heritage. Ultimately, cyber representation expands the scope of conservation practices—transforming heritage from a fixed legacy into an adaptive, living cultural experience that resonates across generations and geographies.

2. State of the Art: Serious Games and Gamified HBIM-VR Workflows for Architectural Heritage

Recent advancements in HBIM and VR have expanded the scope of cultural heritage management—enhancing documentation accuracy, conservation planning, and public engagement [14–17]. HBIM is now a mature methodology for producing precise digital replicas of historic structures, capturing architectural complexity and supporting technical workflows [18]. However, their potential for education, design representation, and public dissemination remains underutilised. Conversely, VR technologies are increasingly leveraged to offer immersive explorations of historical sites, enabling users to interact with reconstructed environments and narratives in ways that were once impossible. Castles and fortifications, with their rich historical and architectural layers, are particularly well suited to these experiences, offering a dynamic approach to cultural preservation.

Many recent developments and studies have demonstrated how immersive VR reconstructions of medieval castles not only improve access to otherwise inaccessible areas but also enhance engagement and deepen educational outcomes [19–30]. These technologies allow for a more nuanced understanding of the spatial and social dynamics that once shaped these iconic structures, offering users a tangible connection to the past that traditional methods of study often cannot provide. In this context, serious games (SGs)—educational games designed beyond entertainment—have emerged as valuable tools [31–33]. They utilize GEs to encourage knowledge acquisition, participation, and emotional connection to heritage. More broadly, gamification strategies are widely applied in cultural heritage to promote visitor interaction, foster interpretation of complex narratives, and increase public appeal. These approaches align with the interdisciplinary field of Virtual Heritage, which merges digital technologies (HBIM, VR, AR, XR) with heritage studies to transform static heritage assets into dynamic, participatory experiences.

Bagnolo et al. [34] propose a hybrid HBIM workflow combining laser scanning, algorithmic modeling, and game environments to increase interactivity and accessibility. Di Paola et al. [35] highlight how narrative-based immersive experiences rooted in VR and AR can center cultural heritage within compelling story frameworks. For gamified applications to succeed, however, strong theoretical underpinnings are essential. Fortes Tondello, Premsukh, and Nacke [36] apply goal-setting theory to gamification, illustrating how feedback systems, achievements, and progress tracking enhance user motivation—principles directly applicable to cultural heritage systems. Systematic reviews further highlight gaps and opportunities in the field. Marques et al. [37] note a predominantly European focus, with many initiatives targeting youth and tourists but lacking methodological consistency. Within the Civitas project, Nespeca [38] demonstrates a multiscale HBIM workflow applied to the Ducal Palace at Urbino, integrating laser scanning, 360° imagery, and high-resolution photography to create a robust model supporting both documentation and immersive storytelling. Smith, Walford, and Jimenez-Bescos [39] compare the deployment of Roman architecture models across game engines, underscoring that accessibility, cost, and usability often outweigh purely visual fidelity when selecting platforms for museums. Similarly, Zheng et al. [40] evaluate platforms for interactive BIM visualization, contrasting the flexibility of WebGL (Web Graphics Library) with the graphical superiority—but higher technical demands—of Unreal Engine. WebGL is a JavaScript API that enables interactive 3D and 2D graphics to be rendered within any compatible web browser without the need for plug-ins, making it particularly suitable for lightweight, cross-platform applications. Their work suggests pixel streaming as a promising solution to improve access by offloading and rendering tasks to a cloud server.

Wang et al. [41] explore how role-playing games (RPGs) based on ancient architecture enhance engagement with cultural heritage, showing that immersion, narrative, and cognitive engagement significantly boost tourists' affective engagement, which in turn supports heritage conservation and sustainable tourism. Theodoropoulos and Antoniou [42] similarly call for interdisciplinary design practices to improve cultural heritage VR applications. Empirical studies such as Vishwanath and Diaz-Kommonen [43] confirm that gamification significantly boosts collaboration and engagement in hybrid learning environments. Looking ahead, Martusciello et al. [44] propose integrating generative AI and AR to enable personalized, adaptive, gamified heritage experiences, significantly advancing digital inclusivity and interaction. Finally, Liu's comprehensive review explores the triadic integration of BIM-HBIM, VR, and gamification [45]. While HBIM offers geometric precision and archival depth, it remains largely inaccessible to the public. When combined with VR and gamified structures—through SGs or narrative-based gameplay—these models can become powerful tools for education and engagement. Liu's study includes a bibliometric review and critical reflection on the effectiveness, tools, content strategies, and future directions of HBIM-driven immersive heritage applications. As the cultural heritage sector continues evolving, the fusion of HBIM with immersive technologies and gamification strategies represents not only a technical advancement but a conceptual reorientation—placing experience, narrative, and accessibility at the heart of digital heritage practice.

3. State of the Art: HBIM Meets Virtual Museums

The direct evolution of the synergistic collaboration between HBIM and VR technologies is embodied in the concept of the virtual museum [46]. HBIM serves as the digital foundation that integrates comprehensive and precise information about the artifact and the built heritage. Meanwhile, VR technologies enable the creation of immersive virtual worlds, elevating the user experience to a highly engaging level. The virtual museum thus becomes a structured and coherent environment, designed to facilitate interaction between HBIM and VR in accordance with the intended visitor experience. This process culminates in a powerful means of dissemination that maximizes virtual visitor engagement, enhancing not only the built heritage but also cultural heritage at large.

The International Council of Museums (ICOM) defines a virtual museum as "a digital entity that draws on museum characteristics to complement, enrich, or extend the museum experience through personalization, interactivity, and rich content." [47]. Virtual museums can host thematic collections—ranging from fine arts and local history to natural sciences and archaeology—or online exhibitions based on documentary sources, much like traditional scientific and educational museums [48]. They may function as digital extensions of existing physical museums, broadening outreach and audience, or exist solely in digital form, composed of interactive 3D models, immersive VR/AR experiences, and digital art installations. Although virtual museums fall under the broader umbrella of digital cultural institutions, they are distinct from digital libraries and online archives primarily due to their communicative, experiential, and immersive nature, focused on interactive storytelling and dynamic cultural heritage promotion, rather than simple digital asset preservation and cataloging. Typically delivered entirely online, virtual museums are referred to by various terms in the literature, including online museums, hypermedia museums, digital museums, cybermuseums, or webmuseums [49]. Their accessibility is notable, overcoming physical, geographic, economic, and cognitive barriers to cultural participation.

International examples demonstrate the innovative potential of virtual museums, as seen in immersive VR experiences by the Louvre in Paris [50] and the British Museum in London [51]. The Louvre's "Mona Lisa: Beyond the Glass, created with HTC Vive, allowed visitors to explore Leonardo da Vinci's masterpiece in unprecedented detail and depth, offering interpretations impossible to achieve in a physical setting. Additionally, the Vatican Museums and the Uffizi Gallery in Italy offer immersive 360° interactive tours of their galleries and chapels, along with curated online exhibitions that enhance user engagement [51,52]. Table 1 provides a concise overview of some of the world's most renowned virtual museums. It lists each museum's location, the type of virtual experience offered—ranging from 360° interactive tours to immersive VR explorations—and direct links to their official online tours [53–61]. The selection highlights a variety of institutions spanning art, history, and culture, showcasing how digital technologies enable accessible and engaging cultural experiences worldwide. The quality of virtual museum experiences has been evaluated through three main aspects. First, the capture method, which refers to the technology used, such as 360° photography, immersive panorama videos, interactive 3D models, Google Street View formats, or complete VR walkthroughs. Second, the resolution and technical quality, which define visual detail and clarity, range from HD to medium-high resolution, including complex 3D models and immersive video formats. Finally, there are additional evaluation factors such as the level of interactivity (free navigation, guided exploration, or limited panoramas), availability of multilingual content, narrative depth through storytelling or cultural context, educational resources, thematic focus (e.g., Renaissance, modern, or religious art), and the overall presentation format. Together, these parameters allow assessment of both the technical quality and the cultural or educational value of each virtual tour.

These virtual museums have made significant progress in delivering immersive experiences through 360° panoramas and high-definition digital tours [62]. Nevertheless, many still fall short in terms of interactivity and depth. Too often, they rely on static visuals or pre-recorded content, providing only limited opportunities for engagement beyond surface-level exploration. What remains underutilized is the powerful potential of integrating HBIM with interactive VR and web technologies to create truly dynamic and participatory cultural environments. A deeper integration of HBIM, VR, and web platforms could transform the way users experience digital heritage. Unlike conventional digital exhibits, this combination allows for real-time interaction with data-rich architectural models, enabling visitors not only to explore historic spaces but also to interact with them meaningfully.

Table 1. Overview of some of the world's most renowned virtual museums, their VR experiences, and official links. It includes the measurement method, resolution/quality, and additional evaluation parameters that describe the type of experience, level of interactivity, and special features available in each virtual tour.

Museum	Location	Type of Virtual Experience	Official Virtual Tour Link	Resolution/Quality	Other Evaluation Parameters
Louvre [50]	Paris, France	360° tours of Egyptian Antiquities, Galerie d'Apollon, Mona Lisa	https://www.louvre.fr/en/online-tours (accessed on 21 August 2025)	High-definition (HD)	Interactive navigation, multiple languages available
British Museum [51]	London, UK	"Museum of the World" timeline tour, high-res galleries	https://britishmuseum.withgoogle.com/ (accessed on 21 August 2025)	High resolution	Storytelling elements, cultural context included
Vatican Museums (incl. Sistine Chapel) [52]	Vatican City	360° interactive tours of galleries and chapels	https://m.museivaticani.va/content/museivaticani-mobile/en/collezioni/musei/tour-virtuali-elenco.html (accessed on 21 August 2025)	High resolution, 3D models	Focus on religious art, detailed imagery
Uffizi Gallery [53]	Florence, Italy	Renaissance art virtual tour	https://www.uffizi.it/en/online-exhibitions (accessed on 21 August 2025)	HD, medium to high quality	Focus on Renaissance artists, limited interaction
Rijksmuseum [54]	Amsterdam, Netherlands	Street-View virtual galleries of Dutch Golden Age art	https://artsandculture.google.com/partner/rijksmuseum (accessed on 21 August 2025)	High resolution	Includes audio guides and information on each artwork
Van Gogh Museum [55]	Amsterdam, Netherlands	Interactive tour with storytelling and artist info	https://artsandculture.google.com/partner/van-gogh-museum (accessed on 21 August 2025)	High resolution	Artist biographies, user interaction through navigation
Natural History Museum [56]	London, UK	Room-by-room 360° tours (Hintze Hall, Dippy)	https://www.nhm.ac.uk/visit/virtual-museum.html (accessed on 21 August 2025)	High resolution	Engaging interactive features for educational purposes
National Museum of Modern & Contemporary Art [57]	Seoul, South Korea	Multi-floor virtual exhibits via Google Arts & Culture	https://artsandculture.google.com/partner/national-museum-of-modern-and-contemporary-art-korea (accessed on 21 August 2025)	Medium to high resolution	Includes artist interviews, exhibition details
The Met 360° Project [58]	New York City, USA	Immersive panorama videos of galleries during off-hours	https://www.metmuseum.org/art/online-features/met-360-project (accessed on 21 August 2025)	HD, immersive quality	Focus on panoramic view, no interaction, video format only
J. Paul Getty Museum [59]	Los Angeles, USA	Virtual tour via Google Arts & Culture, sculpture gardens	https://artsandculture.google.com/partner/the-j-paul-getty-museum (accessed on 21 August 2025)	High resolution	Educational content on sculpture and garden exploration is available
MoMA [60]	New York City, USA	Special exhibition tours and the modern art collection	https://www.moma.org/ (accessed on 21 August 2025)	High resolution	High-quality video tours of specific exhibits
Palace of Versailles [61]	Versailles, France	Full palace VR exploration	https://en.chateauversailles.fr/discover (accessed on 21 August 2025)	High resolution, immersive	Real-time navigation with detailed room information

This kind of environment invites users to engage in active discovery, offering a form of digital storytelling that is both immersive and informative. Several obstacles must be addressed to unlock this potential. Accurate representation of historical and architectural information is essential to maintain the integrity of the content. Additionally, developing digital environments that are accessible across a range of devices and user capabilities requires thoughtful technical planning. Long-term preservation of digital content must also be considered, ensuring that these experiences remain viable despite the rapid evolution of technology.

At the same time, environmental and data sustainability are critical to making this approach responsible and future-proof. Finally, ensuring broad accessibility involves not only removing physical barriers but also addressing cognitive, economic, and social ones.

In this new paradigm, web-based VR plays a vital role in building responsive and engaging virtual museum spaces. By using visual programming tools and low-code environments, professionals from non-technical backgrounds—including curators, architects, and cultural practitioners—can contribute to creating rich, interactive content. Platforms powered by advanced game engines allow for the development of virtual environments populated with sound, motion, and user-driven elements. These features significantly enhance realism and immersion, elevating digital heritage from a passive display to an interactive narrative.

In the context of restoration, this approach opens new opportunities. When real-time data is embedded within immersive models, users can simulate and experiment with restoration strategies in a virtual space. This supports a more collaborative and iterative design process, where decisions can be visualized, tested, and refined before implementation. It also deepens the user's connection to the heritage site, as they are invited to participate in the interpretive and creative process. It is essential to understand that virtual museums are not designed to replace traditional institutions, but rather to complement them by expanding access to and engagement with cultural heritage. Similarly, XR platforms contribute to restoration design by creating collaborative environments where stakeholders can interact with 3D models of heritage sites, enabling more prosperous and more inclusive conservation dialogues. As detailed in Table 2 of this study's comprehensive review, a comparative evaluation of major VR and webVR development tools offers insights into choosing sustainable, accessible, and interoperable HBIM-VR solutions that balance innovation with practicality.

Table 2. Comparative analysis of leading VR and WebVR development platforms for virtual museums.

Platform	Type	Strengths	Limitations	Ideal for...
Unity (WebXR & app) [63]	Professional game engine	Extensive OpenXR/WebXR support, compatible with Quest/PC/standalone, asset store, C# scripting. Ideal for advanced interactions	Longer development time, less performant WebXR in browsers	Robust cross-platform interactive museums
Unreal Engine [64]	Advanced game engine	Photorealism, light-ing/material management, and visual scripting. Sup-ports OpenXR and complex visual logic	Steep learning curve, high hardware requirements	Immersive environments with advanced interactive logic
PlayCanvas [65]	WebXR visual editor	Browser-based visual editor, live updates to headsets, high-performance WebGL/WebXR	Less detailed graphics, simpler interactivity than Unity/Unreal	Lightweight VR tours are easily accessible via a link
Twinmotion [66]	ArchViz + VR walkthrough	Intuitive VR walkthroughs from CAD models, direct sync, realistic materials, and easy to use	Limited interaction, more basic VR features than Unreal	Architectural design reviews in VR, narrative prototyping
SimLab VR [67]	Complete VR platform	Museum-specific: creation, visualization, collaboration, VR layout review	Proprietary model, less customizable than native engines	Interactive digital museums created by teams or with external support

Table 2. *Cont.*

Platform	Type	Strengths	Limitations	Ideal for...
OpenSpace3D [68]	No-code XR engine	Code-free development via visual PlugITs supports OpenXR/Quest/Vive, free and open-source.	Smaller community, limited documentation	Non-technical teams prototyping immersive environments
NeosVR [69]	Social VR/real-time	Build interactive environments and collaborative VR worlds directly in VR, with visual scripting support	Not specific to structured museum exhibits	VR events, social multi-user museums, collaborative labs
Resonite [70]	Hybrid social VR	Edit and build VR environments in-platform; complex interactions via visual scripting.	Social-oriented, requires creative expertise	Participatory museum installations, creative VR labs
Verge3D [71]	WebGL/Three.js WebXR	Real-time interactive web rendering, Blockly visual scripting, Blender/3ds Max/Maya compatibility	Limited real-time rendering, no full native OpenXR VR	Interactive showcases, browser-accessible 3D visual prototypes
Portico [72]	Catalog visualization	Imports digital collections into automatic VR galleries, OpenXR/Quest compatible	Fundamental interactions, limited customization	Dynamic VR exhibitions from museum datasets
VREUD [73]	Web-based authoring tool	Create interactive VR scenes via a browser-based visual tool without coding	Simple scenes, not a complete VR engine	Rapid prototyping of educational VR tours

4. The Municipality of Civitella in Val di Chiana: Geography, Demography and Historical Context

Civitella in Val di Chiana, located in eastern Tuscany within the province of Arezzo, spans about 100 square kilometers and is home to nearly 9000 residents [74]. In 1917, the municipal seat shifted from the historic hilltop town to Badia al Pino in the valley, reflecting broader demographic changes. Despite this, the municipality retained its original name, underscoring the symbolic significance of the historic center, situated 523 m above sea level. The region is characterized by a traditional podere agricultural system, interspersed with olive groves, vineyards, and chestnut forests. In recent years, fruit orchards have diversified the plains, giving the landscape a cultivated, garden-like quality. Settlements follow the valleys and foothills, particularly along the Canale Maestro della Chiana (Figure 1).

Economically, the area strikes a balance between traditional agriculture and modern industry, particularly in the plains, while hill farming has gradually declined. Human presence in the Val di Chiana dates back to the Paleolithic period. During the Iron Age, various populations, including the Ligurian, Umbrian, and Etruscan, coexisted in the region. The Etruscans introduced advanced land reclamation techniques, which were further developed under Roman rule through infrastructure like the Via Cassia road, aqueducts, and the management of the Clanis River. Following the collapse of the Roman Empire, these systems fell into disrepair, and the valley reverted to marshland.

In the Early Middle Ages, insecurity and conflict led to the abandonment of the plains and the rise of fortified hilltop settlements, a process known as incastellamento [75,76]. Civitella's castle likely emerged between the 9th and 10th centuries, built atop earlier Etruscan and Roman foundations. Positioned along vital trade routes, it became both a defensive stronghold and an administrative hub. The town grew in importance under episcopal control but lost its strategic significance after the Battle of Campaldino (1289) and its subsequent annexation by Florence. Key developments such as the Canale Maestro della Chiana (1592) and the construction of Leopoldine farmhouses in the 18th century were part of efforts to reclaim and modernize the territory. The 20th century brought both growth and tragedy—on 29 June 1944, during the German retreat, Civitella was the site of a massacre by the Hermann Göring Division in retaliation for partisan activities. One hundred fifteen civilians were killed, leaving an indelible mark on the community.

(**a**)

(**b**)

Figure 1. Satellite view of Civitella in Val di Chiana from Google Earth Pro (**a**), with the detailed urban landscape of the town, showcasing the heart of this charming Tuscan municipality (**b**).

Today, the castle of Civitella stands as a case study in the integration of digital technologies for heritage conservation. A scan-to-BIM and VR-based workflow supports two key objectives: preparing a restoration and adaptive reuse plan and enhancing accessibility through virtual experiences. Digital reconstruction includes a detailed survey of the existing structure, as well as a hypothetical model of the castle's 13th-century appearance, representing its period of most tremendous significance. This approach not only preserves and disseminates material and historical knowledge but also informs future design interventions.

Recent municipal projects demonstrate a strong commitment to revitalization:

- A pedestrian path was added along the town's outer walls (2020–2021).
- Restoration work improved stair access to the castle's lower levels.
- Funding has been secured for an access ramp to the keep, enhancing physical accessibility.

The next phase focuses on rehabilitating the tower and surrounding structures. Plans include the creation of multifunctional spaces for cultural activities and a panoramic viewing platform. Due to archaeological constraints, no new foundations will be added, and stairways will remain the sole access route. To ensure inclusivity, a virtual museum will be developed within the earthworks. Through immersive technologies, visitors will have the opportunity to explore the tower's architecture and history, regardless of physical limitations. This will make Civitella's rich heritage accessible to a broader audience, both physically and digitally, ensuring that the site's historical narrative is preserved and experienced by all.

5. Materials and Methods: HBIM Models, Historical Reconstruction, and Virtual Accessibility

The Castle of Civitella in Val di Chiana serves as the primary test case for developing and validating this transparent, scalable workflow adaptable to other heritage sites. The cyber-immersive ecosystem is built around three main digital outputs, each playing a distinct but interconnected role in understanding, preserving, and reimagining the site:

As-built HBIM model: This model is generated using high-precision survey techniques such as laser scanning and photogrammetry to capture the current physical state of the castle accurately. It incorporates detailed geometric data, material properties, and structural conditions, providing a comprehensive digital twin of the existing building. This serves as a factual baseline for monitoring deterioration, guiding conservation efforts, and supporting maintenance planning.

Historically informed reconstruction: Grounded in archival research, stratigraphic studies, and expert historical interpretation, this reconstruction envisions the castle as it likely appeared in its peak 13th-century state. It integrates archaeological findings and historical documentation to recreate lost architectural features, original spatial configurations, and period-accurate materials. This model supports a deeper understanding of the site's historical significance and cultural context.

As-designed BIM model: This forward-looking model represents proposed restoration and adaptive reuse interventions, informed by conservation principles and modern architectural strategies. It incorporates design solutions aimed at improving accessibility, structural reinforcement, and functional adaptability while respecting the site's historic fabric. This model enables iterative design testing and visualization of potential future scenarios, helping stakeholders evaluate the impact of different restoration choices.

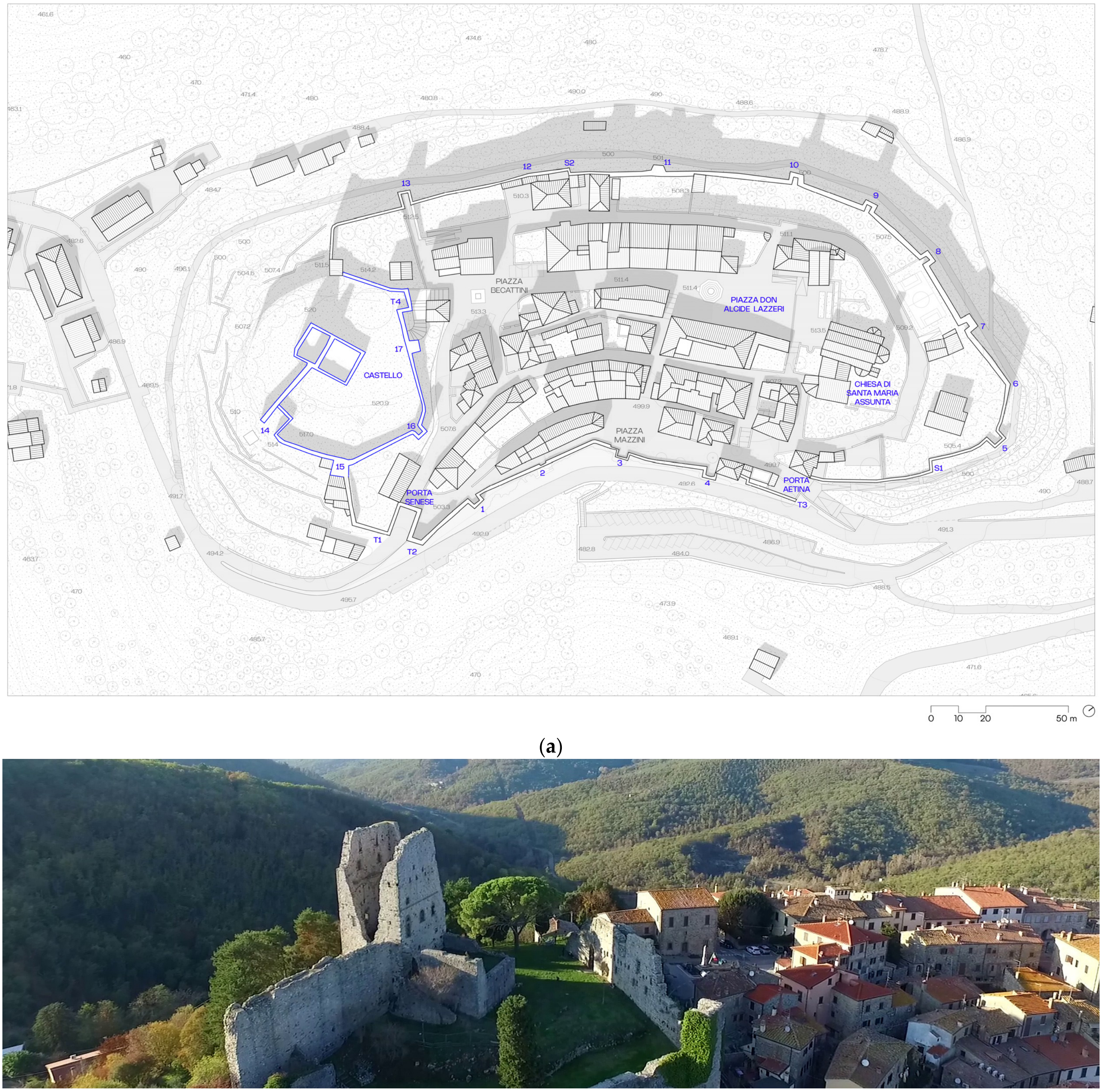
All three models are integrated within a shared immersive platform that enables users to explore, compare, and interact with the castle across multiple temporal layers. By making this cyber-immersive ecosystem publicly accessible, the project encourages inclusive engagement and participatory storytelling, democratizing cultural heritage interpretation beyond traditional institutional boundaries.

5.1. Analysis of the Territorial Setting and the Castle of Civitella in Val di Chiana

The integration between architecture and morphology gives Civitella a compact and harmonious character, where the defensive structures appear as a natural extension of the landscape. The main road axis begins at the central square, where the church of Santa Maria Assunta (13th century) is located, and continues toward the staircase leading up to the castle. There are two historic gates providing access: Porta Aretina, which opens directly onto the square, and Porta Senese, located at the base of the keep, still well preserved and decorated with traces of frescoes. Along these routes, one encounters stone buildings, narrow alleys, and panoramic views opening on both sides of the hill.

The medieval defensive system consists of walls up to 11.40 m high, reinforced by eleven quadrangular towers (Figure 2). Among these, Tower 17, the only closed tower, is near the gate of the keep and preserves original architectural elements such as ogival arches resting on corbels and ancient inscriptions. The curtain wall section between towers 15 and 17 features played loopholes and slots for wooden beams, testifying to medieval construction techniques [77]. The fortified core, the Castellum, is composed of two main structures: the primary one identified as the Palatium-Tower, and a smaller second building used as an entrance enclosure equipped with a cistern for rainwater. Access to the Palatium is designed with defensive criteria, through protected routes with loopholes and walls that forced attackers to expose themselves on the less shielded side. From the inner courtyard, a staircase supported by a flying arch leads to the main entrance, while the walkway connected to the tower by a wooden gangway allows quick isolation of sections in case of attack (Figure 3). The radial wall of the complex shows different construction phases, distinguishable by the stone finishing and techniques used, such as courses of marl limestone and sandstone blocks finished to improve adhesion with mortar. Inside ran the so-called gaina, a vaulted corridor that connected the Palatium to tower 14, now lost, featuring unique loopholes in the Arezzo area. The Palatium, rectangular in shape and about 22 m tall features massive walls with pentagonal towers open inward and equipped with loopholes for flanking fire.

Elements such as the triple series of arches of the entrance door, large sandstone lintelled windows, holes for wooden balconies, and an internal hidden staircase in the thickness of the walls reveal refined military engineering. During World War II, the Palatium suffered severe damage following the English bombing in July 1944, with partial collapses of the southeast and northwest walls (Figure 4). The first restoration intervention took place in 1959, while a much larger and more comprehensive second restoration started in 2019 under the direction of architect Vincenzo Sidoti. The works included the consolidation of the staircase leading to the Rocca, the reconstruction of missing sections of the curtain wall, the restoration of the access arch to the panoramic terrace, and the repaving of the area with carefully selected local stone to preserve the site's authenticity. During the works, a significant triangular architectural element was discovered at the base of a tower, which led to a thorough revision of the initial project, later interrupted due to the COVID-19 pandemic and resulting restrictions that halted construction for an extended period.



(**a**)

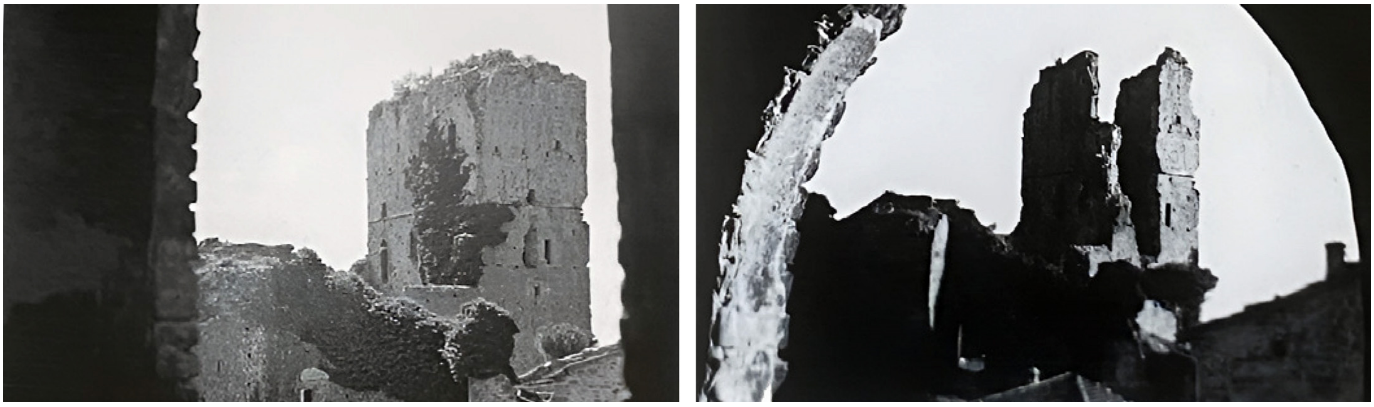
(**b**)

Figure 2. (**a**) Planivolumetric representation of Civitella in Val di Chiana, highlighting the towers and access points of the Rocca di Civitella. Author's elaboration based on [78]. (**b**) A view of the Rocca di Civitella, a historic fortress that dominates the town.

Today, Civitella in Val di Chiana stands as a rare and remarkably well-preserved example of a medieval fortified village, harmoniously integrated into the surrounding Tuscan landscape. Within its walls, architectural testimonies—from defensive loopholes to the characteristic gaina, from imposing towers to monumental historic gates—bear witness to centuries of military history, evolving construction techniques, patterns of social organization, and the rhythms of everyday life that once animated its community.

(**a**) (**b**)

Figure 3. (**a**) Archway leading to the terrace of the lower body after restoration and (**b**) the entrance gate to the cassero, access door to tower 17.



(**a**) (**b**)

Figure 4. The Tower of Civitella before (**a**) and after (**b**) the front line passed through the area (before and after 1944) [Photographs]. Source: Civitella in Val di Chiana Municipality. Civitella in Val di Chiana: Memories and Images of the 20th Century, 152, p. 25, 2022.

5.2. Blending Historical Depth with Cutting-Edge Scan-to-BIM Digital Representations for Immersive Visualization, Rigorous Analysis, and Engaged Heritage Preservation

The approach, which combines 3D survey technologies with information modeling systems, unfolds in four main, closely interconnected phases (Figure 5):

Data Collection: The initial phase involves acquiring data through high-precision digital surveys conducted using the latest 3D survey technologies, integrated with historical sources and archival documentation. The combination of geometric data and historical knowledge enables the construction of a solid and reliable information base.

Modeling (Scan-to-BIM): The methodological core of the process, the modeling phase involves transforming the point cloud into three-dimensional geometries. For complex or irregular elements typical of historic architecture, the use of free-form modeling software such as Rhinoceros v.8 [79] is often necessary. The resulting geometries are then exported into BIM environments—such as Autodesk Revit 2025 [80]—via exchange formats (e.g., .dwg based on the 2007 solids schema), ensuring the consistency and integrity of geometric data.

Information Mapping: Once modeling is complete, the geometric model is enriched with descriptive information: each digital object acquires specific characteristics related to materials, conservation status, construction chronology, uses, etc. This process may include the use of custom parameters (Shared Parameters), manageable through schedules and tables directly within the HBIM environment.

Information Sharing: Finally, an extended sharing strategy was implemented through immersive technologies, enabling more engaging and intuitive access to the digital model. To this end, optimised versions of the 3D models were developed for integration into an immersive ecosystem, using platforms such as Autodesk Revit 2025, Twinmotion and PlayCanvas.

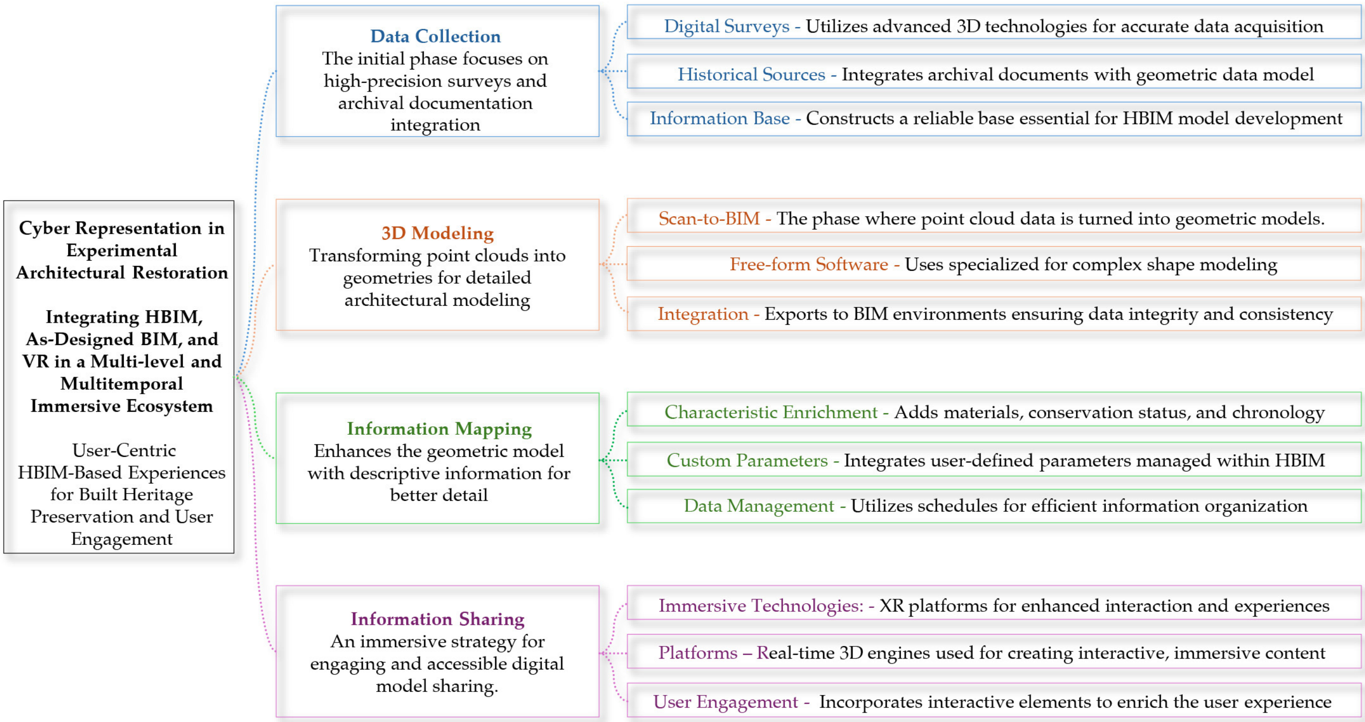


Figure 5. Graphical abstract of the four main phases of the proposed process, highlighting the interconnected stages: Data Collection, Modelling (Scan-to-BIM), Information Mapping, and Information Sharing.

One of the most critical challenges is managing exchange formats effectively. The use of multiple tools and diverse file types can lead to information loss or inconsistencies, making it essential to adopt a well-structured and orderly workflow. The recommended workflow incorporates the following formats:

- Point Clouds: .las, .e57, .pts
- Photogrammetry: .pts, .jpg, .png, .e57
- Drawing and Pointcloud management: .dxf, .dwg, .rcp, .rcs
- Model generation: .3dm, .dwg (2007 solid schema), .sat
- HBIM model: .rvt, .ifc, .xlsx, .fbx, .odbc
- Virtual reality: .fbx, .glb/.gltf, .usd/.usdz, .obj

Establishing a sustainable and integrated development workflow that spans from data acquisition to VR implementation not only enhances the quality and functionality of the digital model but also serves as an effective strategy to preserve, valorize, and share cultural heritage in an innovative and long-lasting way.

The main objective of the digitization process was to preserve and share the uniqueness of the architectural complex, characterized by a curtain wall enclosing the central courtyard, within which three main architectural elements are located: the low building housing the cistern, the hollow tower, and the radial wall that once connected the latter to a now-lost watchtower. To achieve the highest level of accuracy and completeness, a multidisciplinary approach was adopted, combining four main survey techniques:

- **Terrestrial laser scanning**—FARO Focus 3D X 130 HDR (FARO Technologies Inc., Lake Mary, FL, USA) used to acquire high-density point clouds (up to hundreds of millions of points per scan), capturing in detail the architectural and structural geometries of the site.
- **Aerial photogrammetry**—conducted with a DJI Mavic Mini 3 Pro drone(DJI, Shenzhen, China) to document, with high-resolution images (4K, up to 48 MP), the highest and most inaccessible parts of the fortress, ensuring 80% overlap coverage and accurate three-dimensional restitution. Image capture was performed at an average distance of approximately 2 m from the surfaces, both vertically and horizontally, allowing for extremely detailed data acquisition. The intended restitution and representation scales for both 2D and 3D outputs were 1:20, 1:50 and 1:500, which guided the acquisition strategy. Based on these parameters, the estimated image capture accuracy (Ground Sampling Distance) was better than 2 mm/pixel.
- **Terrestrial photogrammetry**—performed with digital cameras, including a Canon EOS 5D Mark IV (Canon Inc., Tokyo, Japan) and a GoPro camera (GoPro Inc., San Mateo, CA, USA), mounted on tripods to capture surface textures and material details both inside and outside, including fragile or partially hidden architectural elements.
- **Topographic survey with total station**—Leica TPS1200 (Leica Geosystems AG, Heerbrugg, Switzerland) used to create a geodetic network of control points, ensuring precise georeferencing of all acquisitions with tolerances of ±2.0 mm for measurements and ±4.5 mm for scan target alignment.

5.3. 3D Surveying, Mesh Retopology, and NURBS-Based Modeling for Historic Architecture: An Integrated Workflow Toward HBIM Implementation

In the context of 3D data management and enhancement, integrating diverse acquisition and processing techniques proved essential to ensure consistency, accuracy, and interoperability across platforms. The approach adopted in this study minimized errors, optimized workflows, and ensured broad data compatibility. Georeferenced point clouds were processed in Autodesk ReCap Pro 2025 [81], converting proprietary formats (.fls, .rcs) into open ones (.e57), ready for integration into software such as Autodesk AutoCAD 2025 [82], Rhinoceros v.8, and Autodesk Revit 2025.

Meanwhile, laser scanning and photogrammetry generated high-resolution polygonal meshes which, despite offering detailed geometry (Figure 6), are not directly suitable for VR environments due to their large file sizes and, especially for curved geometries, high polygon counts—resulting in performance limitations. To address this, a retopology phase was implemented to reduce polygon density while preserving the model's overall shape and proportions. This step was crucial to optimize texture mapping, facilitate rendering, and enable conversion into parametric surfaces for advanced applications. Unlike meshes, NURBS (Non-Uniform Rational B-Splines) allow for a mathematically precise representation of surfaces, with geometric tolerances (Figure 7).

In this project, Grades of Generation (GOG) 9 and 10, based on NURBS patches, were used for representing the complex forms typical of historical architecture while also enabling direct transformation into HBIM objects within Autodesk Revit 2025. As part of the HBIM workflow validation process, a test was carried out to assess the effectiveness of the GOG 10 system in processing and simplifying the 3D model. The test involved the direct integration of the model with point clouds using adaptive deformations, with the goal of optimizing metric consistency between the survey data and the digital model.

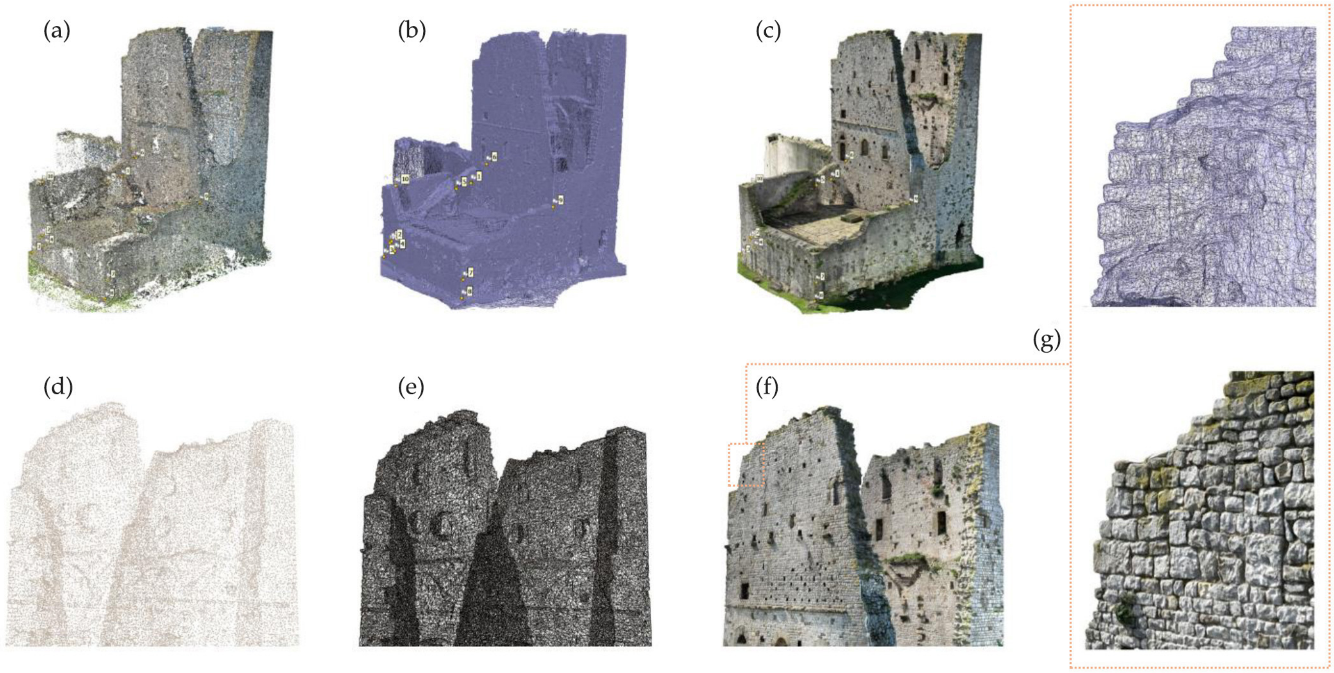
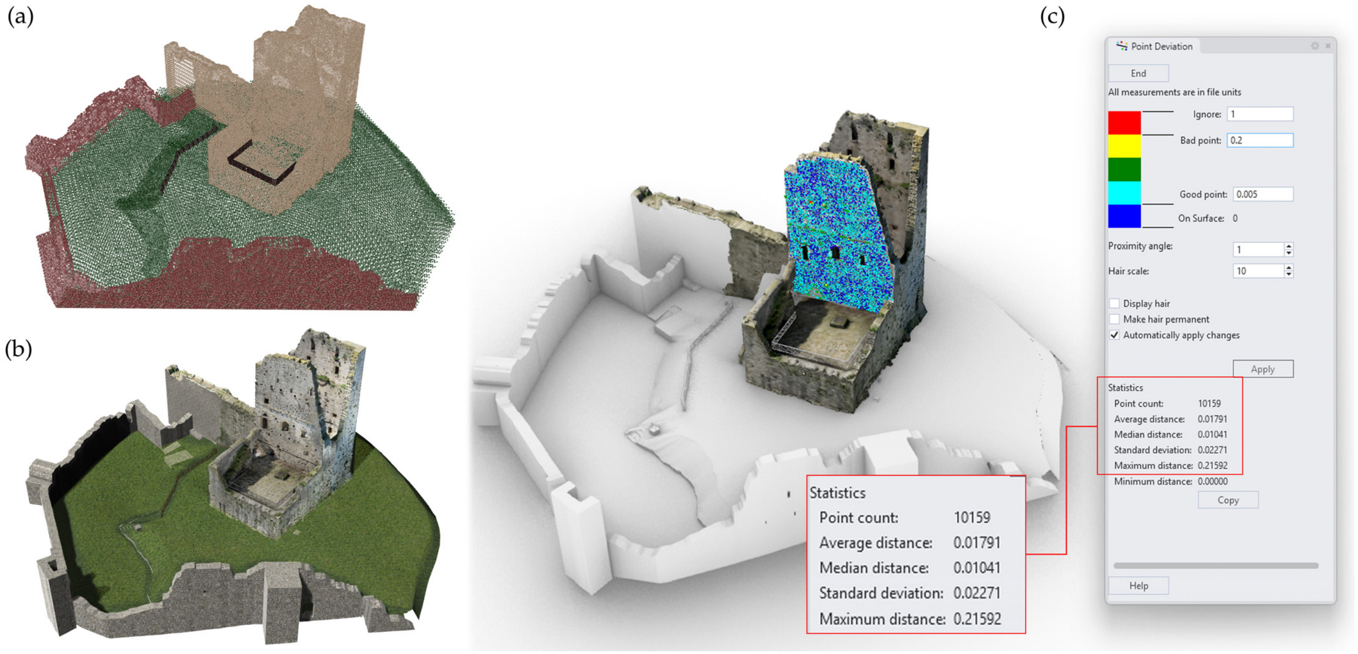


Figure 6. Point clouds (**a**,**d**), mesh models (**b**,**e**), and textured meshes (**c**,**f**). Data acquisition and post-processing laid the foundation for HBIM-based modeling and semantic parameterization of the entire complex, providing basic 3D models with appropriate levels of detail (**g**).



All measurements are in file units

Ignore: 1
Bad point: 0.2
Good point: 0.005
On Surface: 0
Proximity angle: 1
Hair scale: 10

☐ Display hair
☐ Make hair permanent
☑ Automatically apply changes

Statistics
Point count: 10159
Average distance: 0.01791
Median distance: 0.01041
Standard deviation: 0.02271
Maximum distance: 0.21592
Minimum distance: 0.00000

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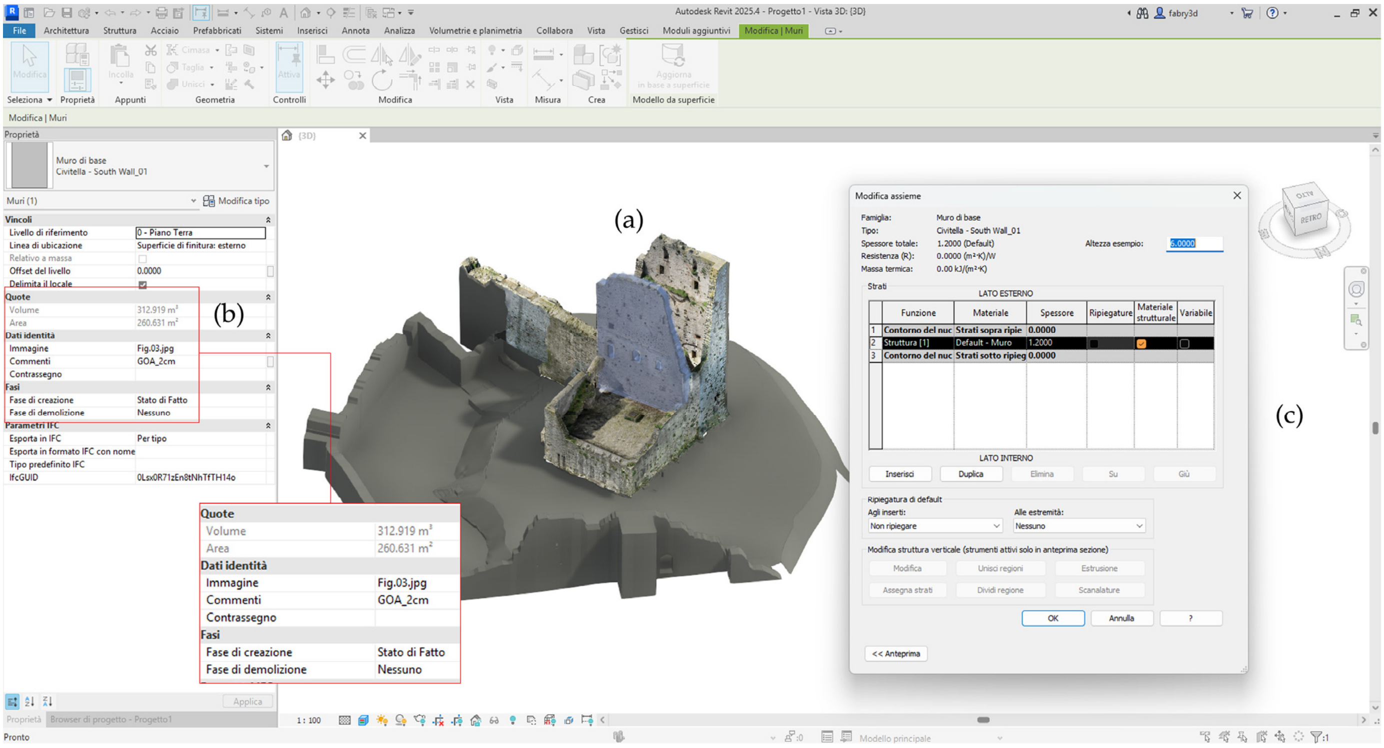
Point count: 10159
Average distance: 0.01791
Median distance: 0.01041
Standard deviation: 0.02271
Maximum distance: 0.21592

Figure 7. The NURBS model (**b**) from pointcloud (**a**), based on a graphical scale of 1:100, excludes elements smaller than 2 cm due to graphical tolerance limits (0.2 mm line thickness × 100). This threshold ensures optimal performance (**c**) in immersive environments while preserving the model's overall metric accuracy.

The test results highlighted the following advantages:

- A significant reduction in the need for manual interventions,
- Improved consistency between the model and the survey,
- A low standard deviation in AVS verification, confirming the model's high metric fidelity.

Subsequently, a conversion test of the HBIM model was performed to evaluate its usability within webVR environments. In this context, a simplification of the model's level of detail was carried out to enhance navigability and graphical performance. The model was adapted to match a graphical scale of 1:100, taking into account the inherent graphical tolerance. This tolerance is linked to the conventional minimum line thickness (0.2 mm), which, when scaled at 1:100, corresponds to 2 cm in the real world (0.2 mm × 100 = 20 mm = 2 cm). As a result, elements or details smaller than 2 cm were intentionally excluded from the simplified version, as they would not be visually distinguishable in a webVR environment at the adopted scale. This approach allowed for a lighter, more stable, and easily navigable model on immersive platforms, while still maintaining a satisfactory level of adherence to the original survey data. To preserve NURBS logic during export, the models were saved in .dwg format using the "2007 Solids" schema, ensuring compatibility with Autodesk Revit 2025, where they were transformed into HBIM parametric objects capable of storing both numerical data (volumes, areas, material properties) and historical/stratigraphic information (Figure 8).



Proprietà

Muro di base
Civitella - South Wall_01

Muri (1)

Vincoli	
Livello di riferimento	0 - Piano Terra
Linea di ubicazione	Superficie di finitura: esterno
Relativo a massa	☐
Offset del livello	0.0000
Delimita il locale	☑
Quote	
Volume	312.919 m³
Area	260.631 m²
Dati identità	
Immagine	Fig.03.jpg
Commenti	GOA_2cm
Contrassegno	
Fasi	
Fase di creazione	Stato di Fatto
Fase di demolizione	Nessuno
Parametri IFC	
Esporta in IFC	Per tipo
Esporta in formato IFC con nome	
Tipo predefinito IFC	
IfcGUID	0Lsx0R71zEn8tNhTfTH14o

Quote	
Volume	312.919 m³
Area	260.631 m²
Dati identità	
Immagine	Fig.03.jpg
Commenti	GOA_2cm
Contrassegno	
Fasi	
Fase di creazione	Stato di Fatto
Fase di demolizione	Nessuno

Modifica assieme

Famiglia: Muro di base
Tipo: Civitella - South Wall_01
Spessore totale: 1.2000 (Default)
Resistenza (R): 0.0000 (m²·K)/W
Massa termica: 0.00 kJ/(m²·K)
Altezza esempio: 6.0000

Strati

LATO ESTERNO

	Funzione	Materiale	Spessore	Ripiegature	Materiale strutturale	Variabile
1	**Contorno del nuc**	**Strati sopra ripie**	**0.0000**			
2	Struttura [1]	Default - Muro	1.2000	☐	☑	☐
3	**Contorno del nuc**	**Strati sotto ripieg**	**0.0000**			

LATO INTERNO

Ripiegatura di default
Agli inserti: Non ripiegare
Alle estremità: Nessuno

Figure 8. The HBIM model is granularly composed of its main architectural and structural elements (**a**), each characterized by a dimensional correlation between numerical data (**b**)—such as area and volume—and typological attributes, including construction phases, materials, and wall stratigraphy (**c**).

This test not only demonstrated the practical advantages of adapting complex HBIM models for virtual environments but also highlighted the importance of balancing graphical fidelity with performance needs. While simplifying the model may result in the loss of some minute details, the interactive nature of webVR and its potential for public engagement and education justifies this trade-off. By ensuring that the core architectural and historical features remain intact, such models can facilitate a deeper, more accessible understanding of cultural heritage, offering a powerful tool for both preservation and virtual tourism. They allow not only specialists but also wider audiences to explore spaces that might otherwise be inaccessible due to geographical distance, conservation restrictions, or safety concerns. This democratization of access strengthens the role of digital technologies in safeguarding collective memory and transmitting knowledge to future generations. Furthermore, this approach opens up new possibilities for the integration of immersive technologies in heritage documentation, creating dynamic and interactive experiences that enhance the visibility and cultural significance of historical sites. Through these tools, heritage can be communicated in a more engaging way, bridging the gap between scholarly research and public dissemination, while also fostering innovative applications in education, museum studies, and cultural promotion. In this sense, immersive HBIM-based models do not simply replicate existing structures in digital form but actively contribute to reinterpreting and revitalizing heritage, ensuring its relevance in an increasingly digital society.

5.4. HBIM and the London Charter in Practice: A Multi-Layered Workflow for the Digital Reconstruction of Historic Architecture

In addition to the as-found HBIM model, a comprehensive analysis was conducted on a wide range of historical and documentary sources, including graphic tables, archival surveys, redrawn plans, historical maps, descriptive texts, and a curated selection of archival photographs. These materials, although heterogeneous in format, scale, dating, and reliability, were critically examined and cross-referenced to establish a consistent and robust information base for the development of the digital model.

The integration of photogrammetric survey data with historical documentation enabled the creation of a three-dimensional reconstruction—albeit simplified—of the architectural and landscape context surrounding the main body of the castle.

What remains today of the castle is only a part of the original complex, which has been partially demolished (especially with regard to the buildings or internal wooden structures), altered over the centuries, and partially dismantled to recover its valuable construction materials. Virtual reconstructions, just like more traditional redrawing methods, are an effective tool for verifying hypotheses, as well as interpreting the signs and traces found in the building (Figure 9).

However, they allow for the model to be modified during the verification phases and to be updated and adapted in the future, based on any new discoveries and knowledge (e.g., archaeological excavations, diagnostic investigations, further surveys. . .). A crucial role in this process was played by Autodesk Revit 2025, which facilitated the simultaneous management of three distinct data layers—the current condition, the reuse design proposal, and the historical reconstruction hypothesis—within a single project file.

Thanks to the use of phasing tools, worksets, and customized visibility controls, it was possible to isolate, compare, and analyze temporal variations of the castle. Autodesk Revit 2025's parametric structure further enabled the incorporation of metadata and historical annotations within modelled elements, effectively transforming the model into an HBIM, following emerging international standards for the digital documentation of cultural heritage. The adopted methodology aligns with the principles set out in the London Charter [78], which provides guidelines for the computer-based visualization of cultural heritage.

The Charter emphasizes the importance of methodological transparency, documentation of sources, representation of uncertainty, and clarity of interpretation. These principles were actively applied in the modeling process: all historically reconstructed components were clearly differentiated using distinct materials and color codes, and each was accompanied by descriptive metadata indicating its level of reliability and the sources used for its definition. The three-dimensional reconstruction of the castle complex—tentatively dated to the 13th century, a period marking the site's historical peak as the permanent residence of the high ecclesiastical court of Arezzo—was conceived with primarily educational and interpretative objectives. While not intended as an absolute or final historical truth, the model represents a research-informed visualization, designed to convey the most plausible architectural configuration of the castle during its period of most significant development, based on currently available data. It is important to note, however, that the degree of uncertainty increases significantly with elevation, due to the limited availability of direct sources and the impact of war-related destruction.

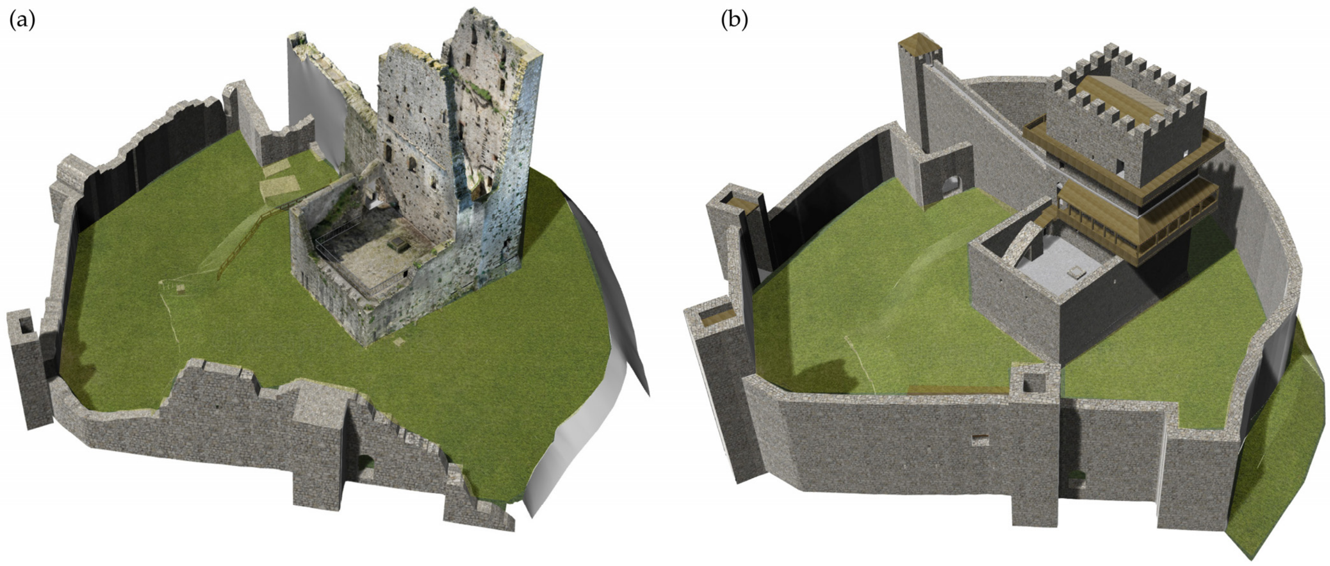


Figure 9. The image illustrates two distinct temporal layers: (**a**) the current physical condition derived from point cloud data and (**b**) a 13th-century hypothetical reconstruction based on critical interpretation of historical sources.

Notably, a cannon strike during World War II severely damaged the main tower, leading to the loss of significant architectural information. The subsequent restoration, carried out in 1959, prioritized structural stability over historical integrity, resulting in the removal of several original material traces. Moreover, the lack of graphic documentation prior to the 20th century further complicated the reconstruction process. The few available historical photographs, together with fragmented written records and 19th-century surveys, were critically interpreted and supplemented through typological comparisons with other contemporary castles in the Val di Chiana region and broader central Italy.

The resulting 3D model, in addition to its technical and scientific relevance, serves an important communicative and cultural function. It is conceived as a dynamic tool for heritage mediation, capable of making complex historical content accessible to a wider audience and supporting decision-making processes related to the preservation and enhancement of the site. The application of the London Charter principles, combined with BIM methodologies, reflects a commitment to responsible documentation, open research, and informed design, wherein digital technologies serve as vehicles for memory, interpretation, and architectural storytelling.

5.5. Information Sharing and Interoperability in Practice: Streamlining HBIM Data for Immersive Experiences Across Unreal Engine, Twinmotion, and PlayCanvas

The methodology behind VR development was grounded in the optimization and repurposing of existing 3D assets, generated initially for HBIM. These models, after undergoing polygonal reduction and texture baking during the retopology phase, were further refined and converted into formats compatible with real-time rendering engines (.fbx, .glb, .gltf, .usd). The immersive deployment was then articulated across three primary platforms, each chosen for its specific strengths in addressing different types of users and technological contexts:

Unreal Engine was utilized for the development of high-fidelity VR applications, capable of delivering realistic lighting, dynamic environmental effects, spatialized sound, and scripted interactions. This platform was particularly suited for producing immersive experiences aimed at professionals involved in restoration planning, architectural analysis, or heritage interpretation. The integration of real-time metrics, guided navigation systems, and layered data visualization made it possible to explore the architectural complex in an intuitive yet analytically rigorous manner. Unreal Engine's flexibility also allowed for the incorporation of custom logic (e.g., visibility filters, chronological reconstructions, stratigraphic layers), adding significant depth to the interpretive experience.

Twinmotion served as a rapid visualization environment, enabling the creation of interactive walkthroughs and scenario simulations with minimal setup time. Thanks to its real-time rendering engine and intuitive interface, Twinmotion allowed for fast prototyping and stakeholder communication, especially in interdisciplinary contexts where architectural content had to be shared with decision-makers, funding bodies, or community groups. Animations, camera paths, and interactive tags were implemented to support narrative sequences and guided explorations, making the tool particularly effective for public presentations and participatory planning processes.

PlayCanvas, an open-source WebGL/WebXR platform, was adopted to deploy the experience directly in web browsers, without requiring any software installation or specific hardware. This allowed for maximum accessibility across devices, including smartphones, tablets, and VR headsets. Through PlayCanvas, a lightweight but functional representation of the 3D model was made available online, enriched with interactive features such as clickable hotspots, contextual pop-ups, and layered thematic content.

The platform's JavaScript-based customization options enabled the creation of educational modules and interactive storytelling sequences tailored to students and general audiences. The XR development process was carefully coordinated with the previous phases of data acquisition, modeling, and information mapping, ensuring semantic continuity across all levels of representation.

Parametric data from the HBIM environment were selectively exported or manually translated to populate the immersive interfaces with relevant metadata—material properties, construction phases, conservation notes, and historical sources. The integration of three distinct platforms for immersive experience development—Unreal Engine, Twinmotion, and PlayCanvas—required a careful and methodical approach to overcoming interoperability challenges. Each platform has specific requirements in terms of input formats, data structuring, material handling, and interaction support, making it essential to define a streamlined and sustainable workflow.

The process began with the creation of a centralized HBIM model, developed primarily in Autodesk Revit 2025 and Rhinoceros v.8 (for NURBS modeling). This model was progressively simplified through UV unwrapping, and texture baking. From this master model, different versions were exported according to the needs of each target platform (Table 3).

One of the main challenges was ensuring consistent material appearance across platforms that interpret PBR (Physically Based Rendering) differently. To address this:

- A standardized PBR workflow was adopted, with materials defined using Base Color, Roughness, Metallic, and Normal maps, exported in .png or .jpg formats.
- In Unreal Engine, materials for complex models were manually rebuilt, while Twinmotion maintained visual fidelity through automatic import via Datasmith [83]. For PlayCanvas, materials were simplified and pre-baked in Blender, using optimized textures to retain as much visual coherence as possible with the other platforms.

Another significant challenge involved the loss of metadata during the transition from HBIM to immersive platforms. While Unreal Engine and Twinmotion can support object-linked metadata via Blueprints [84] or tags, PlayCanvas has limited native support for semantic data structures.

Solutions included:

- Exporting HBIM data to .xlsx and .json, which were then linked to 3D objects in the immersive platforms through scripting (Blueprints in Unreal Engine, JavaScript in PlayCanvas).
- Implementing interactive hotspots and pop-up windows, populated with structured data from external sources or runtime-loaded .json files.
- In Unreal Engine, Blueprint structures were used to manage interactive logic (e.g., displaying historical data on click, highlighting stratigraphic layers, etc.).

Table 3. Export formats and operational workflow for cross-platform interoperability between Unreal Engine [64], Twinmotion [66], and PlayCanvas [65].

Platform	Primary Formats Used	Operational Notes
Unreal Engine	.fbx, .udatasmith, .glb, .obj	Support for PBR materials, lightmaps, custom collisions. The Datasmith plug-in was used for advanced imports from Autodesk Revit 2025 and Twinmotion.
Twinmotion	.udatasmith	Direct export from Autodesk Revit 2025 and Rhinoceros v.8 via the Twinmotion Direct Link plug-in. Real-time synchronization enabled iterative updates.
PlayCanvas	.glb, .gltf	Required extreme polygon optimization (<100 K) and reduced texture sizes. Rhinoceros v.8 was used as an intermediate environment for conversion.

A second phase of development for the Civitella Castle project has shifted its approach by moving away from the initial development in Unreal Engine and adopting Twinmotion for the immersive visualization. This decision was made to enhance the sustainability of the process and align it more effectively with the Autodesk Revit 2025 BIM environment through the use of the Datasmith add-in. Twinmotion was chosen primarily for its ability to offer a smooth, real-time rendering experience while also ensuring compatibility with BIM workflows, which are vital for the ongoing restoration planning and future adaptive reuse.

Twinmotion enables a better integration between the BIM model and the visualizations, thanks to its seamless connection with Autodesk Revit 2025. The platform's real-time rendering engine is particularly well-suited for balancing both visual quality and performance. This made it an ideal choice to replace Unreal Engine for this phase of the project, which was previously optimized for desktop VR headsets but placed a heavier demand on hardware. By moving to Twinmotion, the project becomes more accessible to a wider range of users, as it requires less powerful systems while still maintaining high-quality visual outputs.

In addition to Twinmotion, PlayCanvas was also explored for web-based interactive experiences. Due to the hardware limitations of web platforms, this required the application of aggressive mesh simplification techniques in Blender, including decimation algorithms and normal baking. Textures were also compressed for web delivery, ensuring optimal performance on various devices, with a maximum of 2 K resolution and .jpg progressive or .webp formats. This approach ensures that the web experience remains fluid and visually appealing without compromising performance.

These varying platforms required separate strategies to guarantee optimal performance and visual output for different user environments. By using the most appropriate software for each scenario, the project can cater to a broad range of users and devices, from high-end VR headsets to more accessible web-based experiences. This flexibility also enables different types of users—such as researchers, architects, educators, students, and the general public—to access the content according to their needs and available technology. This immersive, multi-channel strategy greatly enhances the project's ability to break free from the limitations of static documentation.

By integrating interactive, real-time visualizations with traditional data-sharing workflows, the project fosters a deeper experiential understanding, spatial awareness, and emotional engagement with the heritage site. Visitors can navigate the site virtually, explore its architecture, and gain insights into the restoration process in a much more intuitive and engaging manner. Moreover, this approach also increases the project's reach and impact, contributing to the valorization, dissemination, and long-term digital preservation of Civitella's cultural heritage.

The shift to Twinmotion and web-based platforms ensures that the project is not only sustainable and aligned with modern BIM practices but also adaptable to various technological environments and user profiles. This will ensure that the digital preservation of Civitella's castle can be maintained for future generations, accessible to a wide audience, and integrated into educational and research contexts.

5.6. Toward the Enhancement and Adaptive Reuse of the Castle of Civitella in Val di Chiana Through an Inclusive, Multisensory VR Approach

Over the past 25 years, the Castle of Civitella in Val di Chiana has been the focus of various studies and design proposals that have contributed to a deeper understanding of its historical, architectural, and symbolic value. Despite differing in scope and methodology, these initiatives shared the common aim of revitalizing a ruined yet highly evocative structure. The current project builds on this legacy, integrating past insights with contemporary cultural and technological perspectives. Three major proposals between 2002 and 2020 significantly shaped the castle's recent design discourse. The first, by Enzo Sacchetti [85], was a thesis project involving rigorous surveys, critical research, and a 3D reconstruction of the castle's medieval form. Presented through comparative visuals, this speculative model exemplified a "cognitive restoration" approach, emphasizing documentation and historical interpretation rather than construction. The second, led by Professor Carmela Crescenzi in 2006, proposed a lightweight steel structure with panoramic walkways connecting the tower's summit. Though conceptually intriguing, the lack of detailed documentation left the project unrealized [77]. The third, by architect Vincenzo Sidoti (2019–2020), envisioned a glass and steel core within the existing tower walls, supporting a new staircase and viewing platform. It also included a digital museum at the base and a new passage through the radial wall. However, archaeological discoveries of ancient foundations and the outbreak of the COVID-19 pandemic halted its development.

Despite this, the project's goals—public accessibility, cultural reuse, and reinterpretation—remain central to current efforts (Figure 10). In close collaboration with the Municipality, the latest intervention targeted the recovery of the tower and its surrounding structures. Key objectives included enhancing accessibility and transforming the space into a venue for exhibitions, educational activities, and community events. New internal floors symbolized a metaphorical ascent, culminating in a panoramic belvedere enriched by VR experiences. Three architectural components were prioritized: the main tower, the lower structure in front of it, and the "gaina" corridor within the radial wall. Though built in different historical periods, the current project reinterpreted them as interconnected elements within a unified and dialogic design strategy. The lower structure was converted into a digital exhibition space using VR and AR technologies, while the gaina, previously undocumented, was surveyed and made partially accessible via a new entry point at the tower's base. Archaeological excavations in 2020 revealed substructures likely of Etruscan or Lombard origin, ruling out the addition of new foundations. In response, the new structural interventions were anchored to existing masonry, requiring targeted consolidation due to damage from WWII bombings. Two structural strategies were adopted: a partial material reconstruction of missing sections to restore visual continuity, and a reversible internal structure that preserved historical "scars" as visible traces of the site's past. To address serious threats from atmospheric agents, several protective measures were implemented, including the removal of vegetation accompanied by anti-regrowth treatments, the installation of a sealed floor system integrated with the historic walls, and the creation of a rainwater drainage system that relies on hidden outlets, collection channels, and underground conduits.

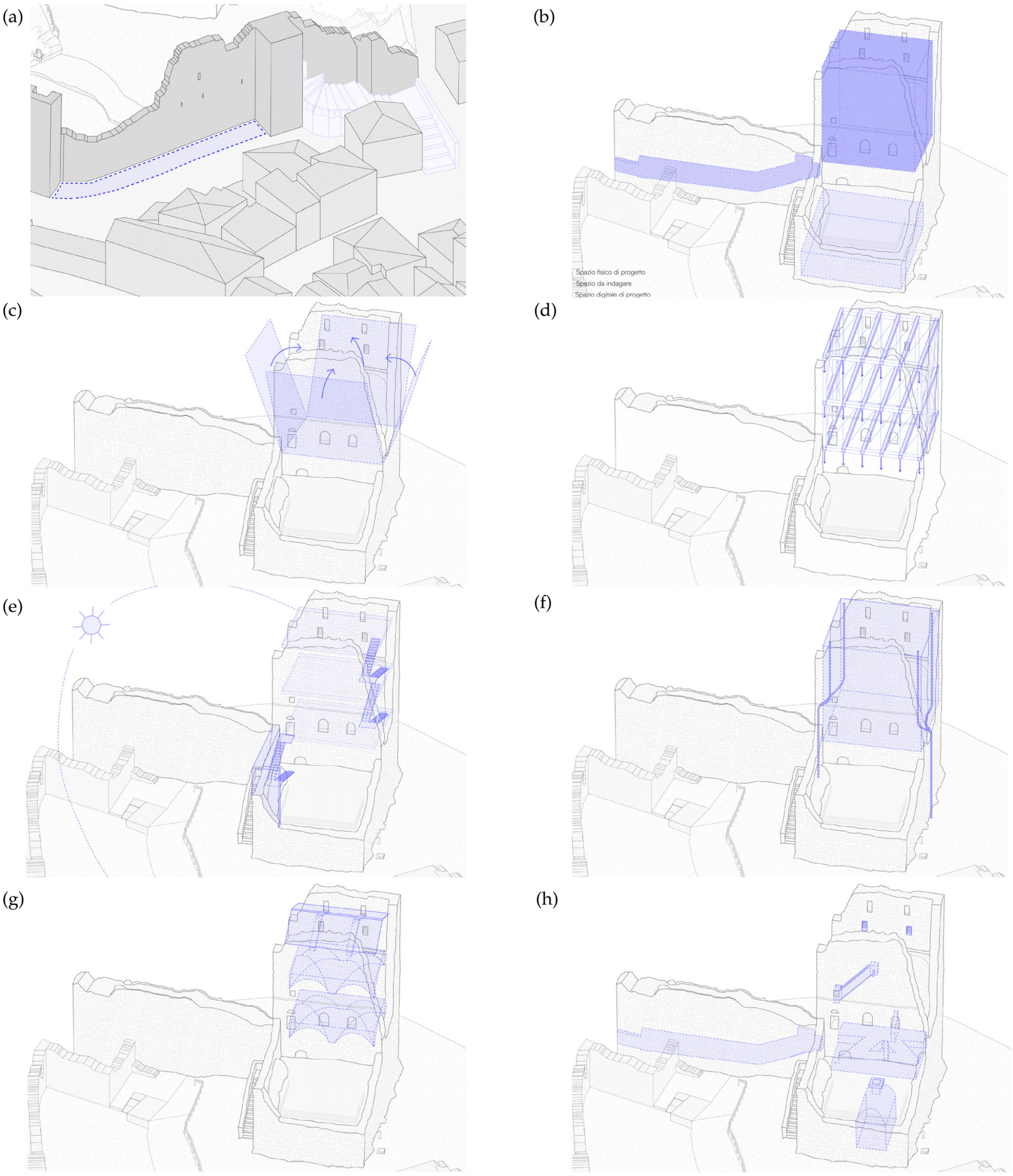


Figure 10. Development and analysis of project requirements and critical points through the multi-phasing tool of the as-designed HBIM model: (**a**) Representation of the need for an access ramp (left) and the existing staircase (right); (**b**) Identification of the three key areas requiring intervention; (**c**) Representation of the need for box-like structural solidity of the existing walls; (**d**) Hypothesis of a structure anchored to the existing masonry; (**e**) Requirement for vertical circulation both outside and inside the tower, along with solar trajectory analysis; (**f**) Need to protect interior surfaces from weather exposure and explore possible rainwater drainage solutions; (**g**) Deteriorated historical elements of which only traces remain; (**h**) Existing historical elements requiring dissemination and further study.

A key enabler of this integrative approach was the adoption of parametric digital modeling and advanced data management, which allowed the coexistence and coordinated management of multiple as-designed BIM model states within a single multi-level project file. Utilizing a scan-to-BIM process, the as-found condition was rigorously documented and modeled from dense point cloud data, capturing the current physical and structural realities of the castle with high metric accuracy.

This foundational model provided a precise baseline from which design interventions and historical reconstructions could be developed in parallel.

The parametric environment—primarily realized through Autodesk Revit 2025—facilitated the layering of distinct temporal phases: the as-found (existing conditions), the as-designed (future reuse proposals), and the hypothetical historical reconstruction (based on archival research and archaeological findings).

Through worksets, phasing tools, and customized visibility controls, project stakeholders could isolate, compare, and analyze the different states of the castle seamlessly within the same digital workspace. This multi-layered modeling approach not only enhanced coordination among architectural, archaeological, and engineering teams but also supported comprehensive documentation and decision-making workflows.

Moreover, the integration of metadata and historical annotations within parametric elements ensured that each model component was semantically rich, linking geometric data with material properties, construction chronology, conservation status, and source reliability.

This digital framework aligned with international standards for HBIM and embodied principles of transparency and interpretive clarity advocated by charters such as the London Charter. By enabling simultaneous visualization and management of all phases—past, present, and future—the parametric model became an indispensable tool for conservation planning, heritage interpretation, and community engagement, ultimately transforming the Castle of Civitella into a living digital heritage asset. Beyond physical restoration, digital enhancement played a central role in the project. Immersive technologies enabled the virtual reconstruction of lost or hidden architectural elements—such as cross vaults, staircases, and the radial corridor—without replacing the tangible experience. Instead, these tools fostered a layered, interactive storytelling environment that bridged memory, innovation, and engagement. By integrating HBIM and VR, the castle was reimagined not only as a preserved monument but as a dynamic platform for cultural participation. The result is an inclusive, multisensory experience that deepens understanding of Civitella's complex identity through time.

6. Interactive VR and Immersive Ecosystems for Cultural Heritage Management

The rapid evolution of digital technologies has fundamentally transformed the way cultural heritage is managed, allowing for the creation of new, innovative methods in design, interaction, interpretation, and preservation. These advancements have paved the way for more engaging and effective approaches to not only documenting and preserving cultural heritage but also presenting it in interactive and immersive forms. Among these innovations, interactive VR and immersive ecosystems—integrating VR, HBIM, and adaptive storytelling—are at the forefront, revolutionizing the traditional methods of cultural engagement. These systems create rich, multisensory environments that transcend the conventional role of passive project visualization and instead actively involve users, fostering a deeper sense of inclusion and participation (Figure 11). By creating more accessible and engaging ways for people to interact with cultural content, these technologies help ensure that heritage is not only preserved but also experienced in a meaningful way.

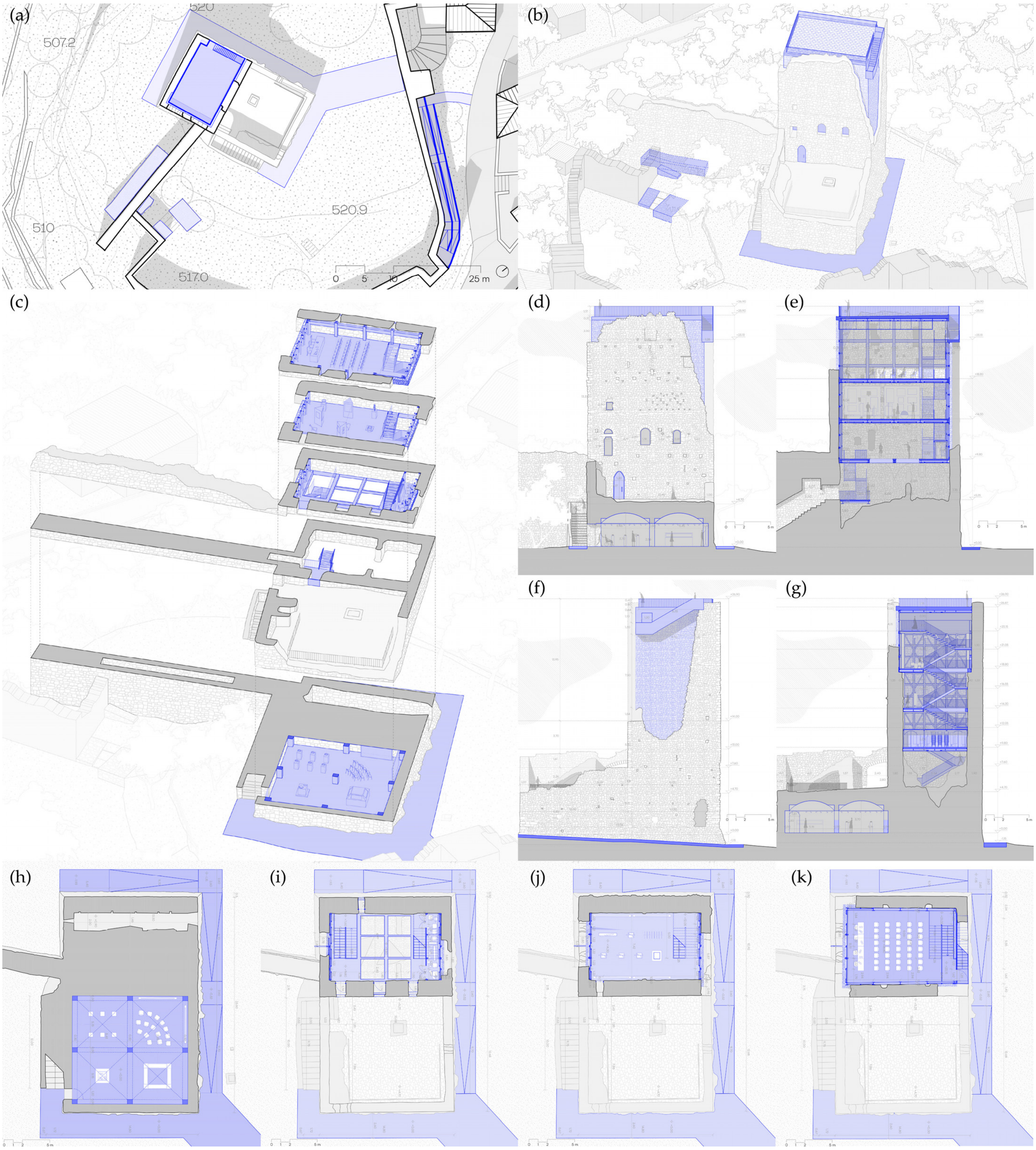


Figure 11. Overview of the as-designed HBIM model within a multilayered and multitemporal design approach: the HBIM model operates in constant alternation between the as-found state and the as-designed vision—addressing functional requirements and proposing interventions. (**a**) Volumetric site plan; (**b**) Axonometric view from the east side, featuring stone-filled basins with original materials from the tower; (**c**) Exploded axonometric view showing spatial hierarchy; (**d**) North-East section at the first level; (**e**) Full North-East section of the building, integrating structural assessment with new intervention layers; (**f**) North-West elevation, revealing the interplay between preserved and redesigned elements; (**g**) North-West section, tracing vertical connectivity across different time periods; (**h**) Ground floor plan; (**i**) Second floor plan; (**j**) Third floor plan; (**k**) Fourth floor plan.

The hybrid ecosystems enabled by these technologies facilitate dynamic and complex interactions between the digital and physical realms. In these systems, virtual reconstructions and designs go beyond serving merely as visual representations of architectural or historical structures; they evolve into interactive, narrative-driven spaces that engage users in ways that traditional media or static representations cannot. Users are given the freedom to explore, manipulate, and even reimagine the environments and histories they are interacting with, allowing them to experience layered and multifaceted stories in ways that were previously unimaginable. This immersive and participatory approach empowers users to become active participants in the process of historical exploration, giving them the agency to uncover deeper layers of meaning and connection with the past. This not only enhances their understanding of the cultural material but also enables them to engage with history in a deeply personal and experiential way. Within this innovative framework, interactive VR plays a crucial role in enhancing narrative immersion, making users feel as though they are physically present in the historical or cultural narratives being presented. The user is no longer a passive observer but an active participant in the story, which significantly deepens their engagement.

Meanwhile, the broader immersive ecosystems go beyond visual and auditory stimuli by integrating sensory design elements such as touch, movement, and even scent, creating a truly multi-sensory experience. The integrated ecosystem itself refers to a complex and interconnected system of technologies, tools, and methodologies working synergistically to manage, restore, and enhance cultural heritage, while also facilitating its storytelling. At the core of successful immersive storytelling is a compelling narrative structure, grounded in the five essential questions—Who, What, Where, When, and Why—which guide the user through a rich, engaging journey of discovery:

- Who: The protagonists include historic architecture, past inhabitants, scholars, and contemporary users. The visitor's avatar acts as a symbolic agent for narrative interaction.
- What: The story unfolds through VR/webVR, blending sensory engagement and interactive digital objects within immersive virtual environments (IVE).
- Where: Set in the Castle of Civitella in Val di Chiana, the reconstruction uses 3D scans, HBIM, as-designed BIM models, and archival research for historical accuracy.
- When: The narrative spans both historical timelines and the present, bridging past and future through XR tools.
- Why: The project aims to valorize heritage and engage diverse audiences, using technology as a narrative vehicle that is evocative, participatory, and emotionally resonant for both the current and historical reconstructions

This method aligns with current research (e.g., Banfi, 2023) [29], which highlights Virtual Visual Storytelling (VVS) as one of the most effective strategies for heritage communication. VVS treats storytelling not as support content, but as the experience itself—using digital proxemics, an avatar in a first-person template, and dynamic virtual objects to generate rich, interactive environments.

6.1. From the As-Designed BIM Model to the Representation of the Restoration Project Through VR

The VVS of Civitella's castle builds upon extensive research by architect Enzo Sacchetti, who conducted detailed analyses of its construction phases and adaptive changes. His critical interpretations of structural irregularities became the foundation for a layered digital model designed as a narrative experience—where present ruins contain echoes of past lives, much like a matryoshka (Figure 11).

The project was developed to encompass both on-site and on-line experiences. Visitors navigate a virtual journey through eight checkpoints, each tied to a specific architectural or historical moment, arranged vertically from the castle's base to its panoramic terrace (Figure 12).

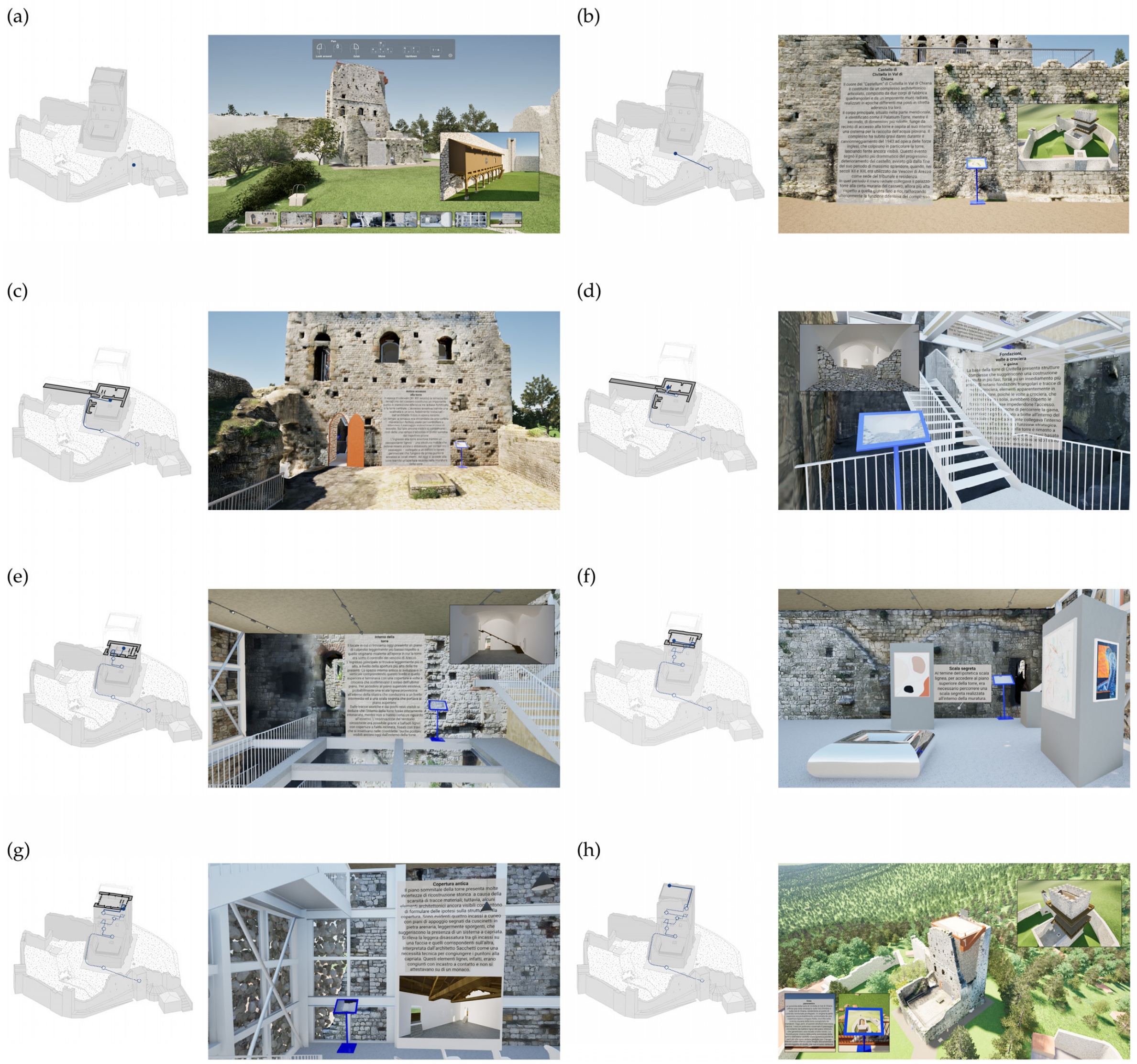


Figure 12. Virtual Visual Storytelling (VVS) of the Castle of Civitella in Val di Chiana developed in Twinmotion [66]: Through specific checkpoints, users can navigate within the VR and WebVR environment of the castle's restoration project and its 3D reconstruction. The experience includes: (**a**) Minor entrances and architecture, (**b**) Castle of Civitella in Val di Chiana, (**c**) Ancient access to the tower, (**d**) Foundations, vaulted ceilings, and 'gaina' structure, (**e**) Interior of the tower, (**f**) Exhibition space and secret staircase, (**g**) Ancient roofing, (**h**) Panoramic view and overall historical reconstruction.

Each checkpoint is enriched with detailed annotations and integrated into a Twinmotion-based digital platform, offering a dynamic and interactive environment. The model is enhanced by a 3D reconstruction videos, providing a deeper historical interpretation that extends beyond academic and specialist audiences. This approach makes historical knowledge more engaging and accessible, bridging the gap between scholarly research and public engagement. The project combines rigorous historical investigation with immersive design, enabling new forms of cultural participation.

Through its thoughtfully designed narrative and interface, the experience transforms heritage into an inclusive, multisensory, and emotionally resonant journey—merging physical and digital realms, connecting memory with innovation.

The integration of advanced technologies allows users to explore historical content in ways that engage both the intellect and the emotions, making history come alive in new and interactive forms. A key objective of the eight checkpoints is to offer varied interaction modes tailored to site-specific features, allowing users to meaningfully engage with the Castle of Civitella in Val di Chiana's complex structure.

Given the site's monumental scale and intricate architecture, it was crucial to develop a navigation framework to guide users through the virtual environment. This structure ensures that users can engage with the castle's history and architecture in ways that highlight its diverse facets, from its foundational layers to its more recent historical layers.

Figure 13 illustrates how users, guided by an intuitive interface, can navigate the virtual environment using desktop PCs, mobile devices, or cutting-edge VR headsets. Through controllers and keyboards on desktops, touchscreens on mobile devices, or immersive VR headsets, the developed VR ecosystem ensures a seamless experience across multiple devices, making it accessible to a wide audience for both remote and on-site exploration. This flexibility allows users to access the site from different locations and devices, ensuring that the cultural experience is inclusive, engaging, and educational, regardless of physical or technological limitations. Moreover, the adaptability of the system enhances user engagement by offering personalized interaction methods that suit various preferences and accessibility needs. This capability not only broadens the reach of cultural heritage preservation but also ensures that the experience remains dynamic and interactive, making it a valuable tool for both scholarly research and public engagement.

(**a**) (**b**)

Figure 13. The developed interaction modes encompass various VR environments designed to ensure different levels of accessibility and user engagement: desktop PCs, laptops, and mobile devices such as tablets and smartphones, enabling both web-VR access (**a**) and a fully immersive VR experience, navigable with the latest VR headsets (**b**).

6.2. VR Development of the Castle of Civitella in Val di Chiana with PlayCanvas: A Web-Based Approach

The digital enhancement project of the Castle of Civitella in Val di Chiana involved the use of the PlayCanvas platform for the development of an interactive VR experience accessible via the web. The choice of PlayCanvas was driven by the primary objective of ensuring maximum accessibility and dissemination of the experience, overcoming the limitations imposed by standalone and desktop-based solutions. The development process of the model, originally created in Rhinoceros v.8 and Autodesk Revit 2025, serves as an example of how digital technologies can be utilized for the enhancement of cultural heritage through easily accessible tools.

The first phase of the process involved exporting the 3D model from Autodesk Revit 2025, primarily used for architectural design and BIM data management. Since PlayCanvas does not directly support Revit's native formats, the model was exported in FBX format, which allows for the preservation of relevant information regarding geometry, materials, and textures, necessary for subsequent rendering. The model was then optimized using modeling software such as Blender and 3ds Max, which reduced the complexity of geometries and improved texture distribution to ensure faster and smoother loading within the PlayCanvas environment.

The optimization phase also included the simplification of more complex geometries and texture management, with the goal of minimizing computational load during the model's web visualization. Once optimized, the model was exported in the glTF format, chosen for its lightweight nature and native compatibility with PlayCanvas. The glTF format was used to ensure efficient management of 3D data, with the ability to transfer geometries, materials, and animations in a single file. Importing into PlayCanvas involved assigning textures to the respective objects, with the addition of specific interactions such as informative hotspots and environmental dynamics to simulate changing light throughout the day.

The use of PlayCanvas enabled the creation of an interactive experience through JavaScript scripts, allowing users to explore the castle. Specifically, the camera management and scene movements were configured to enable smooth and immersive navigation, with support for VR devices compatible with WebXR. In terms of performance, LODs were adopted to display lower-detail versions of objects depending on their distance from the camera, significantly reducing rendering load. Additionally, culling was implemented to avoid rendering objects outside the user's view, and occlusion culling was used to hide objects behind others, further optimizing performance.

The final step of the process involved the publication of the project on the PlayCanvas [65] platform, which offers a native hosting system for 3D projects, allowing users to access the experience directly through a web browser. The result was a 3D model of the Castle of Civitella that was not only interactive but also easily accessible to a broad audience without the need for expensive devices or dedicated software. This approach made cultural heritage truly open and usable, overcoming the limitations of standalone VR platforms and offering an effective alternative for consumption by users on PC, mobile devices, and VR headsets.

Despite the challenges related to optimization and graphical quality compared to more traditional solutions like Twinmotion, the choice of PlayCanvas proved to be successful from an accessibility standpoint, ensuring a democratized experience of cultural heritage in a global context, free from technological barriers.

The advantages of PlayCanvas over Twinmotion include:

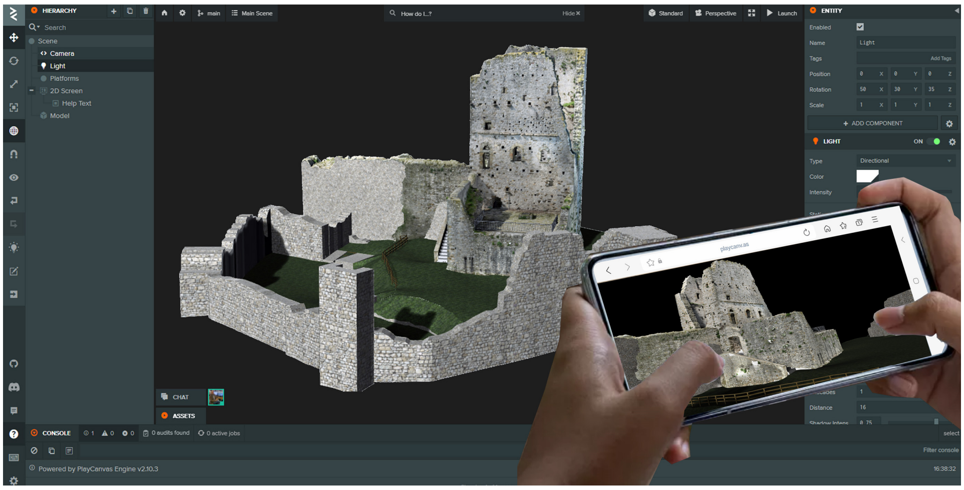
- Immediate browser-based accessibility: Unlike Twinmotion, which requires downloading an application or executable package, PlayCanvas allows access with a simple link, making sharing extremely fluid.
- VR experience on WebXR: PlayCanvas supports WebXR, allowing immersive navigation even through web-compatible headsets such as Meta Quest, directly from the headset's browser.
- Real-time collaboration: The online editor allows multiple developers to work simultaneously on the project, facilitating rapid iterations and shared updates.

Despite these advantages, Twinmotion proved to be more performant in the following aspects:

- Graphical quality and realism: Twinmotion, being based on Unreal Engine, offers a higher level of graphical detail and realistic lighting, which is particularly useful for high-impact visual presentations.
- Optimization time: To ensure smooth performance in the browser, significant efforts were made to simplify the models and reduce textures, which can limit the visual fidelity compared to the original.
- Integrated architectural features: Twinmotion provides specific tools for the architectural environment (weather animations, automatic population, etc.) that must be manually recreated in PlayCanvas.

Despite some graphical limitations compared to Twinmotion, the choice of PlayCanvas was still strategic for the widespread and inclusive dissemination of the VR experience of the Castle of Civitella in Val di Chiana. Unlike standalone VR platforms, which require dedicated devices and technical knowledge for installation, the web-based approach ensures access to anyone with a modern browser, on PC, smartphone, or headset.

This eliminates barriers to entry, allowing users with varying levels of technical expertise to engage with the experience seamlessly. In this way, cultural heritage becomes truly open and accessible, enhancing historical memory through the most democratic technology: the web (Figure 14).



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Name Light
Position 0 X 0 Y 0 Z
Rotation 50 X 30 Y 35 Z
Scale 1 X 1 Y 1 Z
LIGHT ON
Type Directional
Distance 16
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Powered by PlayCanvas Engine v2.10.3
16:38:32

Figure 14. The PlayCanvas [65] interface displays the Castle of Civitella in Val di Chiana project in the editor, with visible textures, lighting, and interactive features. In the foreground, a mobile device shows a user navigating the 3D model, exploring rooms and viewpoints, while interacting with hotspots that provide detailed historical and architectural information. This highlights PlayCanvas' web-based, interactive potential for immersive cultural experiences.

7. Discussion

This research highlights the transformative role of the Science of Representation in enabling virtual accessibility to build heritage, showing how digital and immersive technologies—such as HBIM, historical reconstruction, and virtual reality (VR)—can broaden engagement with architectural history.

These technologies redefine representation, extending it beyond documentation to become an active mediator in the exploration of heritage sites. This shift is exemplified by the Civitella Castle case study in Val di Chiana, Italy, where a fractal restoration approach allows for multilevel, multitemporal engagement with the site. Users can explore both the structure's historical evolution and its present condition, offering a dynamic understanding of the built environment that traditional 2D representations could not.

The integration of advanced scan-to-BIM processes created a high-fidelity immersive ecosystem, providing a scientific foundation for future restoration efforts. More importantly, this system enables virtual access to spaces that are otherwise physically inaccessible, deteriorated, or restricted due to preservation regulations, democratizing access to cultural heritage.

The study argues that the evolving role of digital tools in heritage conservation shifts how we conceptualize and interact with heritage. Unlike previous technological advances—such as the shift from manual drafting to CAD—this new paradigm redefines design thinking. Digital tools now act as mediators between the physical and the digital, facilitating a richer, more inclusive understanding of architectural heritage. Transitioning from static 2D representations to immersive 3D environments enables users to actively engage with heritage sites in ways traditional documentation could not.

Additionally, this approach enhances the hermeneutic process of interpreting historical narratives, allowing users to interact with the site and unveil new layers of history, offering kaleidoscopic perspectives that merge technology, history, and human interaction. From a social and cultural perspective, virtual accessibility enabled by these immersive technologies holds significant value. Sites that are difficult to access due to geographical, physical, or legal barriers can now be experienced by a wider public, including those with physical disabilities.

These technologies foster more resilient and sustainable cultural engagement, broadening opportunities for diverse public interaction with heritage sites.

Looking forward, this research advocates for integrating digital tools into broader heritage conservation and education strategies, emphasizing collaboration with local authorities, such as the Municipality of Civitella in Val di Chiana, to incorporate these tools into sustainable heritage management practices. The combination of digital representation and virtual access provides new models for heritage valorization that can be replicated in different cultural contexts. Ultimately, this study positions the Science of Representation as a transformative force that reshapes how we preserve and experience architectural heritage. In this context, the future development of tools like Rhinoceros v.8 and Autodesk Revit 2025, combined with advanced rendering engines such as Unreal Engine, will enhance the connection between 3D modeling and immersive visualization.

Continued improvements in VR and AR compatibility will push the boundaries of interactive design, enabling architects and heritage conservationists to explore new ways of engaging with built heritage. The choice between tools like PlayCanvas, Twinmotion, and Unreal Engine depends on the project's needs. PlayCanvas is ideal for lightweight, web-based projects, while Twinmotion and Unreal Engine provide high-quality, immersive visualizations suited for advanced VR experiences. When integrated with Rhinoceros v.8 and Autodesk Revit 2025, these tools create a seamless workflow between detailed 3D modeling and immersive visualization.

This combination will enable the creation of high-fidelity digital environments that support restoration design and offer new ways to interact with heritage sites. As these technologies evolve, greater synergy between modeling and visualization will enable more precise, interactive, and inclusive experiences, becoming essential components of broader cultural heritage preservation strategies. This will lead to more dynamic, multifaceted engagements with architectural history.

Despite these promising advancements, several challenges remain. The connectivity and latency issues associated with HBIM models oriented toward WebXR platforms currently require optimization, particularly in terms of model size and data management.

Large-scale and detailed HBIM datasets often necessitate phases of model simplification and data compression to enable smooth real-time interaction and accessibility over web networks. This necessity limits the immediacy of fully immersive experiences and calls for further research into efficient streaming and rendering techniques.

Moreover, while immersive platforms increase accessibility, they also pose technological barriers related to hardware capabilities and internet speed in certain regions, which could affect equitable access. Additionally, the integration of diverse data types—ranging from laser scans to photogrammetric models and historical archives—demands robust interoperability frameworks, which are still evolving.

Future developments should therefore focus on refining these technical aspects, advancing compression algorithms, optimizing network protocols, and expanding user interface design to ensure that the full potential of integrated digital workflows can be realized in diverse contexts and for a broad audience

8. Conclusions

This research positions digital technologies not merely as passive tools of representation, but as active agents in reshaping the epistemology of design. Within the context of architectural heritage, the convergence of physical and digital domains enables a design approach that is both analytical and speculative: restoration is no longer understood as a static act of conservation, but as a dynamic process shaped by data, simulation, and interpretive experimentation.

A key element of the proposed innovation lies in the adoption of an integrated digital workflow, starting with a scan-to-BIM process that enables accurate modeling of the current state based on laser scanning and photogrammetric survey data. This model becomes the foundation for integrating historical reconstructions, design proposals, and museum content into immersive environments developed using Unreal Engine, Twinmotion, and PlayCanvas. This approach goes beyond the limitations of static 3D models by offering an interactive and narrative experience articulated across multiple temporal layers: the current condition of the Castle of Civitella in Val di Chiana, its historical transformations, and speculative design interventions. Moreover, the integration of a virtual museum within the same digital ecosystem enhances user engagement by offering a participatory and emotionally resonant experience, opening new possibilities for education, civic involvement, and cultural tourism.

Methodologically, this research introduces a multitemporal and multilevel framework that integrates as-found documentation, historical reconstructions, and design proposals into a single interactive model. This layered system allows for the coexistence of different temporal states of the site—past, present, and future—and provides a practical tool for comparative analysis, design decision-making, and interdisciplinary collaboration.

The use of Virtual Reality (VR) further expands the role of digital tools as narrative media, enabling users to explore the historical evolution of the site while projecting themselves into possible futures through experimental design. In this way, VR does not merely visualize architecture—it narrates it, activating a critical dialogue with the site's transformation.

The adoption of WebVR platforms such as PlayCanvas represents a significant shift in terms of practicality and accessibility. These platforms allow immersive experiences to be accessed directly from standard web browsers and everyday devices—laptops, tablets, smartphones—without the need for expensive headsets or dedicated installations. This makes virtual exploration of heritage scalable and inclusive, overcoming economic, geographical, and technological barriers, and aligning with contemporary goals of equity and participation in cultural dissemination.

The case study of the Castle of Civitella in Val di Chiana demonstrates how this approach can redefine restoration as a forward-looking and design-oriented practice. The integration of digital and immersive representations enables new forms of engagement with heritage—not only as memory, but as material for design, education, and cultural communication.

Looking ahead, the proposed methodology offers a replicable and scalable model for cultural heritage valorization. Collaborating with local institutions—such as the Municipality of Civitella—could support the integration of these digital strategies into broader cultural planning and territorial development initiatives. Ultimately, this research advocates for a design culture in which restoration is not a final goal, but an evolving and participatory process. When meaningfully integrated, digital tools have the potential to bridge disciplinary divides and redefine the relationship between heritage, design, and society.

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