Virtual Archaeology Review, **16**(32): 44-70, 2025
https://doi.org/10.4995/var.2024.22628

Received: October 16, 2024
Accepted: January 12, 2025

UNLOCKING THE INTERACTIVE POTENTIAL OF DIGITAL MODELS WITH GAME ENGINES AND VISUAL PROGRAMMING FOR INCLUSIVE VR AND WEB-BASED MUSEUMS

DESBLOQUEO DEL POTENCIAL INTERACTIVO DE LOS MODELOS DIGITALES CON MOTORES DE JUEGOS Y PROGRAMACIÓN VISUAL PARA MUSEOS INCLUSIVOS DE VR Y WEB

Fabrizio Banfi[a,*], Daniela Oreni[a]

[a] Politecnico di Milano, Department of Architecture, Built Environment and Construction Engineering, Via Ponzio 31, 20133 Milano, Italy. fabrizio.banfi@polimi.it; daniela.oreni@polimi.it

Highlights:

- Digital surveying, Historic Building Information Modeling, Game Engines and visual programming are enhancing virtual reality technologies, turning static models into engaging, interactive virtual environments (IVE)
- A VR app and WebVR application have been developed for the Ospedale Maggiore in Milan, integrating virtual-visual storytelling (VVS) with three-dimensional (3D) animations, textual information, and audio to enhance user engagement
- The VR and WebVR solutions support a wide range of devices, making cultural heritage more accessible to diverse audiences and promoting a more inclusive understanding of history and architecture

Abstract:

In an era marked by rapid digital transformation, the preservation and dissemination of cultural heritage increasingly depend on advanced technologies to convey both its tangible and intangible values, whether on-site or remotely. Monuments, archaeological sites, historical centres, and museums are progressively recognising the transformative potential of extended reality (XR) technologies. Among these, virtual reality (VR) has emerged as a particularly effective tool for communicating information and engaging visitors. These technologies facilitate the creation of immersive, interactive experiences that provide access to vast datasets, often difficult to explore within the limitations of physical settings. This study investigates these emerging paradigms, specifically focusing on the roles played by digital surveying, data interpretation, Historic Building Information Modelling (HBIM), and visual programming languages (VPL) in developing innovative VR solutions. These advancements allow for the transformation of static BIM into dynamic interactive virtual environments (IVE) and virtual objects (IVO), which respond to user input in real-time, thereby fostering engaging and dynamic digital experiences. A case study of the Ospedale Maggiore in Milan—designed by Filarete in the mid-15th century and currently housing the University of Milan—serves as an exemplary model of the potential of these technologies. A VR platform and a WebVR application have been developed, enabling users to immerse themselves in a virtual environment enriched by virtual-visual storytelling (VVS). This narrative approach integrates textual information, audio, and 3D animations to enhance the user's experience (UX) and provide a multifaceted understanding of the site's historical and cultural significance. By supporting a diverse range of devices—including desktop computers, VR headsets, and mobile phones and tablets—these solutions aim to expand accessibility, foster inclusivity, and promote a deeper, more immersive engagement with cultural heritage. The project not only enhances the visitor experience but also advances the role of digital technologies in democratising access to and understanding of cultural and historical resources.

Keywords: virtual reality (VR); interactivity; visual programming language (VPL); historic building information modelling (HBIM); WebVR, game engine (GE); user experience (UX)

Resumen:

En una era marcada por una rápida transformación digital, la preservación y difusión del patrimonio cultural dependen cada vez más de tecnologías avanzadas que permitan transmitir tanto sus valores tangibles como intangibles, ya sea de manera presencial o remota. Los monumentos, sitios arqueológicos, centros históricos y museos están reconociendo progresivamente el potencial transformador de las tecnologías de realidad extendida (XR). Entre estas, la realidad virtual (VR) ha surgido como una herramienta particularmente efectiva para comunicar información y captar la atención de los visitantes. Estas tecnologías facilitan la creación de experiencias inmersivas e interactivas que permiten acceder a grandes volúmenes de datos, a menudo difíciles de explorar dentro de las limitaciones de los entornos físicos. Este estudio investiga estos paradigmas emergentes, con un enfoque específico en los roles que desempeñan el levantamiento digital, la interpretación de datos, el *Historic Building Information Modelling* (HBIM) y los lenguajes de programación visual (VPL) en el desarrollo de soluciones innovadoras en VR. Estos avances permiten transformar BIM estáticos en entornos virtuales

*Corresponding author: Fabrizio Banfi, fabrizio.banfi@polimi.it

interactivos (IVE) y objetos virtuales (IVO) que responden en tiempo real a la interacción del usuario, promoviendo así experiencias digitales dinámicas y cautivadoras. Un estudio de caso del *Ospedale Maggiore* en Milán, diseñado por Filarete a mediados del siglo XV y actualmente sede de la Universidad de Milán, sirve como modelo ejemplar del potencial de estas tecnologías. Se ha desarrollado una plataforma VR y una aplicación WebVR que permiten a los usuarios sumergirse en un entorno virtual enriquecido por una narrativa visual-virtual (VVS). Este enfoque narrativo integra información textual, audio y animaciones 3D para mejorar la experiencia del usuario y proporcionar una comprensión multidimensional de la importancia histórica y cultural del sitio. Al ser compatible con una amplia gama de dispositivos, incluidos ordenadores de escritorio, visores VR y teléfonos móviles y tabletas, estas soluciones buscan ampliar la accesibilidad, fomentar la inclusividad y promover un compromiso más profundo e inmersivo con el patrimonio cultural. El proyecto no solo mejora la experiencia del visitante, sino que también impulsa el papel de las tecnologías digitales en la democratización del acceso y la comprensión de los recursos culturales e históricos.

Palabras clave: realidad virtual (VR); interactividad; lenguaje de programación visual (VPL); modelado de información de edificios históricos (HBIM); WebVR; motor de juegos (GE); experiencia del usuario (UX)

1. Introduction

In recent years, game engines (GE) and virtual reality (VR) have emerged as a transformative force in the visualisation and dissemination of cultural heritage, fundamentally reshaping how historical sites, museums, and artefacts are preserved, interpreted, and experienced (Rodriguez-Garcia, Guillen-Sanz, Checa & Bustillo, 2024). These innovative technologies go beyond the confines of traditional representation methods, breaking down geographical and physical barriers to transport users on immersive journeys through time. They offer an experience that not only reconstructs the past but makes it tangible, allowing anyone to traverse epochs, explore distant worlds, and interact with history directly and vividly as if it were present to be discovered. Their transformative power not only challenges the limits of reality but rewrites the very rules of our relationship with the past, inviting us to experience stories never told in such a complete and engaging manner (Buragohain, Meng, Deng, Li, & Chaudhary, 2024; Chen, 2024; Liu, Sun, & Shidujaman, 2024).

This shift heralds new paradigms, such as digital proxemics, heightened interactivity (Yang, Huang, Feng, Hong-A, & Guo-Zhong, 2019) and interdisciplinarity the latter of which fosters a synergy of diverse expertise, making the creation of immersive experiences an essential competency in an increasingly digitised world (Adams, Feng, Liu & Stauffer, 2021).

The creation of advanced VR experiences demands expertise from a range of disciplines, including architecture, engineering, and archaeology, as well as advanced proficiency in software development and computational modelling (Loup, George, Marfisi & Serna, 2018). This interdisciplinary knowledge is crucial for embedding dynamic behaviours into digital models, enabling them to respond to user inputs in real-time within interactive virtual environments (IVE) (Rubio-Tamayo, Gertrudix Barrio & García García, 2017). As a result, interactivity has become a focal point of research in digital heritage modelling.

This shift represents a significant advancement for professionals in digital representation, archaeology, heritage conservation, and virtual museums. Interactive models go far beyond static geometric depictions, offering a more immersive, dynamic, and multifaceted representation of cultural and historical narratives, enriching our understanding and engagement with the past.

Recent scholarship has underscored the centrality of interactivity and perception in extended reality (XR) applications (Alhakamy, 2024), particularly concerning Building Information Modelling (BIM) (Alizadehsalehi, Hadavi, & Huang, 2021). The integration of BIM within VR environments offers numerous advantages, such as enhanced project communication, the development of more engaging museum exhibitions, and broader accessibility to information, both on-site and remotely (Sidani, Dinis, Sanhudo, Duarte, Santos Baptista, Pocas Martins & Soeiro, 2021). Moreover, VR fosters inclusivity by accommodating users of varying technical proficiencies, with different entry points via VR headsets, desktops, and mobile devices.

This broad accessibility allows VR to democratise the cultural heritage experience, inviting a more diverse audience to engage with history in dynamic, personalised ways.

At the core of this digital evolution lies the imperative for professionals to acquire advanced competencies in digital drawing techniques, 3D modelling, and immersive environment design. These skills are essential for conveying heritage values and crafting interactive experiences catering to diverse users and devices (Rossi & Armellino, 2023; Fitria, 2023; Coburn, Freeman & Salmon, 2017).

In this context, the ability to transition fluidly between traditional BIM platforms—such as Autodesk Revit and Graphisoft ArchiCAD—and immersive technologies within XR environments has become a critical skill for professionals seeking to remain at the forefront of their fields. The integration of these technologies allows traditional practitioners to expand into new disciplinary domains, thereby addressing the demands of the digital era.

This convergence significantly enhances the accessibility, perception, dissemination, and inclusivity of their work, fostering broader engagement and understanding within diverse audiences (Giordano, Russo, & Spallone, 2023; Salerno, 2019; Hu-Au & Lee, 2017; Pan, Cheok,Yang, Zhu & Shi, 2006). When it comes to building heritage, established methodologies such as HBIM (Murphy, McGovern & Pavia, 2009), terrestrial laser scanning and close-range photogrammetry (Grussenmeyer et al., 2011; Lerma Garcia, Navarro, Cabrelles, & Villaverde, 2010), and scan-to-BIM approaches have long been essential for the documentation and preservation of heritage sites (Rocha, & Mateus, 2021; Brumana, Tucci, & Lerma, 2019).

HBIM models, by their nature, are static representations that limit the potential for public engagement, falling short of fully capturing the immersive experience of interacting with and perceiving space. In contrast, the shift toward dynamic and interactive VR platforms revitalises historical data, transforming it into a compelling and engaging experience that reaches a broader and more diverse audience.

This research aims to overcome the limitations of traditional approaches by proposing a sustainable, interdisciplinary framework that maximises inclusivity while minimising operational inefficiencies. By harnessing the power of game engines (GEs) and dynamic VR platforms, the study seeks to democratise access to cultural heritage, making it more immersive, accessible, and relevant to contemporary audiences.

This approach acknowledges the challenges inherent in the digital transition, particularly the complexities of adapting existing workflows to modern technologies. A key focus of the study is the Ospedale Maggiore in Milan, a 15th-century historical building designed by Filarete. Through VR, users can explore the evolution of this architectural masterpiece—from its original design to its post-World War II reconstruction—navigating its courtyards and uncovering significant archaeological remains. This immersive methodology not only redefines how history is experienced, but also provides a multifaceted exploration of the past while preparing the virtual environment for future exhibitions.

The study explicitly examines how different forms of data sharing and digital representation, especially HBIM, can be enhanced through visual programming languages (VPL) and advanced VR technologies (Jungherr & Schlarb, 2022; Andrade, 2015). The objective is to create customisable, interactive VR platforms accessible to various audiences, whether at home, in educational settings, or within professional environments. This flexibility addresses key challenges in the digital preservation of cultural heritage, facilitating the creation of interactive, semantically rich HBIM models that bridge traditional documentation methods with immersive, user-centred experiences.

Ultimately, this research advocates for a paradigm shift in heritage management that fosters inclusivity, encourages public participation, and strengthens our connection to history. The case study of the Ospedale Maggiore serves as a prime example of how standalone and web-based VR applications can transform our engagement with cultural heritage, offering a framework for future developments in this rapidly evolving field.

The research is structured to provide a concise review of the state-of-the-art in HBIM, model interactivity, VPL, GEs, and VR applications in virtual museum practices, followed by a detailed analysis of the historical context surrounding the case study. The methodology emphasises user interaction with digital models, while subsequent sections explore the results, focusing on visualisation, perception, and the experiential value of the VR environments. This study also discusses the potential of future applications, positioning interactive representation and VR as transformative forces in managing and disseminating cultural heritage.

2. State of the art and research objectives: from HBIM to advanced VR interactions for heritage sites and virtual museums

In the recent decade, the enhancement of cultural heritage has undergone a radical transformation thanks to the adoption of advanced digital technologies and methodologies. Among the most significant in this context are HBIM, game engines, and advanced VR applications. These forms of virtual representation not only improve the process of documentation and visualisation of heritage but also offer new ways to interact with it, making cultural heritage more accessible to a broader and more diverse audience. This brief state-of-the-art explores the evolutionary path from HBIM to advanced GEs and VR solutions, analysing the latest innovations and their impact on the management and dissemination of cultural heritage.

2.1. The emergence of HBIM as a tool for cultural heritage

HBIM is a methodology that has emerged since 2009 as an extension of BIM, specifically designed for the conservation and management of built heritage (Banfi, 2016; Quattrini, Malinverni,Clini, Nespeca & Orlietti, 2015; Oreni, Brumana, Della Torre, Banfi, Barazzetti, & Previtali, 2014; Nieto Julián & Moyano Campos, 2014; Murphy, McGovern & Pavia, 2009). It emerged as a natural extension of the widely adopted BIM, which had already revolutionised the design and management of modern buildings (Pavan, Mirarchi, & Giani, 2017; Cocchiarella, 2016; Sdegno, 2016; Osello, 2012). BIM facilitated the creation of intricate 3D models that seamlessly integrated structural, technical, and management information (Tang, Shelden, Eastman, Pishdad-Bozorgi & Gao, 2019). However, the need for a tailored approach became apparent as the focus shifted to historical structures.

HBIM arose to address this demand, introducing a level of complexity necessitated by the unique characteristics of ancient buildings—often marked by irregular geometries, historical materials, and distinctive construction techniques (Banfi, Dellù, Roncoroni & Cacudi, 2024; Nieto-Julián, Farratell, Bouzas Cavada & Moyano, 2023; Liu, Azhar, Willkens & Li 2023; Maiezza & Tata, 2021). At its core, one of the most compelling advantages of HBIM lies in its unparalleled ability to integrate and process a variety of data types (Pepe, Costantino, & Restuccia Garofalo, 2020; Georgopoulos, & Stathopoulou, 2017; Fai & Sydor, 2013; Remondino, & Rizzi, 2010; Quintero, Blake, & Eppich, 2007). This includes photogrammetric surveys, 3D laser scans, various historical documents, architectural drawings, and other heterogeneous sources (Giordano, 2019; Bertocci & Parrinello, 2015; Barsanti, Giner & Rossi, 2022).

Numerous significant studies explore various themes within this field (Rocha, Mateus, Fernández, & Ferreira, 2020). Some researchers focus on the relationship between HBIM and the BIM Execution Plan (BEP), examining its implementation (Martinelli, Calcerano, & Gigliarelli, 2022; Heesom et al., 2021). Other studies emphasise building life cycle management and energy analysis (Calcerano et al., 2024; Di Biccari et al., 2022; Nagy & Ashraf, 2021).

Additionally, a substantial body of work is devoted to applying HBIM to historic infrastructures (Cruz, Cabaleiro, Conde, Barros, & Riveiro, 2024; Xu; Gómez, Adineh, Rahrig, & Lerma, 2024; Conti, Fiorini, Massaro, Santoni, & Tucci, 2020). Additionally, research on the scan-to-BIM process for structural analysis using point clouds (Lo Presti et al., 2024; Abbate, Invernizzi, & Spanò, 2022; Ursini, Grazzini, Matrone, & Zerbinatti, 2022; Rolin, Antaluca, Batoz, Lamarque, & Lejeune, 2019; Trizio, Savini, Giannangeli, Boccabella, & Petrucci, 2019; Bassier, Hadjidemetriou, Vergauwen, Van Roy, & Verstrynge, 2016; Barazzetti et al., 2015; Dore et al., 2015) has gained attention.

Moreover, some studies explore integrating computational methods, programming, and machine learning techniques for optimising scan-to-BIM workflows (Moyano, Musicco, Nieto-Julián, & Domínguez-Morales, 2024; Croce, Caroti, Piemonte, De Luca, & Véron, 2023; Park, Kim, Lee, Jeong, Lee, Kim, & Hong, 2022; Perez, Golparvar-Fard, & El-Rayes, 2021; Lo Turco, & Tomalini, 2021). Other areas of interest include the application of photogrammetry in archaeological studies (Banfi, 2020; Trizio & Savini, 2020; Scianna, Gagli, & La Guardia, 2020; Diara & Rinaudo, 2020), and the concepts of Level of Development (LOD) and Level of Accuracy (LOA) (Nieto-Julián, Farratell, Bouzas Cavada, & Moyano, 2023; Castellano-Román, & Pinto-Puerto, 2019; Chow et al., 2019; Bruno et al., 2018; Brusaporci, Maiezza, & Tata, 2018; Brumana et al., 2018).

These techniques provide invaluable tools for accurately capturing cultural landmarks' physical and historical characteristics, ensuring their conservation for future generations (Lovell, Davies, & Hunt, 2023). Through the creation of accurate HBIM, stakeholders can gain a comprehensive understanding of a building's conservation state, trace its historical transformations, and identify any necessary interventions (Oreni, 2023; Jordan-Palomar, Tzortzopoulos, García-Valldecabres, & Pellicer; 2018). This multidimensional view fosters informed decision-making, allowing conservators and architects to engage with the past while planning for the future.

Despite advancements, HBIM use has mainly been limited to specialists like architects, engineers, and conservators, excluding non-specialist audiences from engaging with the rich information within these models. This restricts public interaction and creates a disconnect between technology and the wider community. Additionally, the static nature of HBIM, which capture heritage at a specific moment, fails to convey history's dynamic, evolving narratives. They lack the interactive elements expected in today's digital age. The lack of interactivity in HBIM becomes evident as immersive storytelling gains prominence in cultural engagement (Bekele et al., 2018; Gladstone & Stasiuli, 2017). Most HBIM applications are confined to desktop environments, lacking user-driven experiences. A shift is needed to unlock HBIM's full potential.

Recent studies have explored moving HBIM into IVEs to expand its use in entertainment, museums, and education (Banfi 2023; Conde et al., 2023; Lumini, 2023). These studies show how integrating VR and WebVR transforms static HBIM into dynamic virtual worlds, fostering deeper public engagement with cultural heritage. Non-specialists can use VPL to interact with HBIM, creating and customising their experiences without extensive technical skills. This democratisation of technology allows broader public participation in heritage conservation.

2.2. The evolution of VR for heritage sites: from the adoption of VR in AEC projects to virtual heritage

Integrating immersive technologies, particularly VR, into the Architecture, Engineering, and Construction (AEC) industry has gained significant traction in recent years. A growing body of research has explored VR's potential to enhance various facets of AEC workflows, particularly improving communication, facilitating design reviews, and fostering stakeholder collaboration. These advancements highlight VR capacity to transform traditional practices by providing more interactive, visual, and data-driven decision-making and project management platforms.

A systematic review by Wen & Gheisari (2020) underscores the complexity of the AEC sector and illustrates how VR can serve as a crucial tool for streamlining communication among project participants. The review indicates that VR applications have significant promise for enhancing project communication efficiency by providing immersive, real-time visualisation environments. Furthermore, Wu, Hou, & Zhang (2021) categorise XR applications within BIM into distinct functions, such as task guidance and process management, thereby establishing a framework for future exploration in this field.

Research on VR potential in AEC extends beyond communication to project management and training areas. Zhang, Liu, Kang & Al-Hussein (2020) conducted a bibliometric analysis of 229 journal articles, identifying trends and gaps in VR research within the built environment. They propose future research directions that include user-centred design and construction training systems incorporating human factors, thereby pushing the boundaries of how VR can transform the industry. Alizadehsalehi, Hadavi, & Huang (2020) also emphasise VR educational advantages, particularly in enhancing students' comprehension of complex designs and fostering creativity.

However, challenges remain; for instance, Noghabaei, Heydarian, Balali & Han (2020) highlight the slow adoption of VR and AR in the AEC sector, attributing this to a lack of comprehensive cost-benefit analyses. Moreover, Sidani, Dinis, Sanhudo, Duarte, Santos Baptista, Pocas Martins & Soeiro (2021) point out the absence of standardised assessment methodologies for VR implementation in AEC projects, indicating the need for more robust evaluation frameworks. The existing literature on VR in the AEC industry illustrates its potential to revolutionise traditional workflows, yet significant exploration is still needed. While the benefits of VR—such as improved communication, enhanced project management, and innovative educational tools—are straightforward, further research is essential to address limitations, including high costs and technical challenges, as well as the need for standardised methodologies for implementation and assessment.

Moving forward, efforts should focus on refining VR technologies to ensure seamless integration with BIM and other industry tools. Additionally, exploring the synergy between VR and emerging technologies like HBIM, AR, and AI could provide new avenues for innovation. By tackling these challenges and advancing the state of the art, VR has the potential to become a cornerstone of the AEC industry's digital transformation, driving unprecedented efficiency, collaboration, and creativity (Safikhani, Keller, Schweiger & Pirker, 2022).

Integrating HBIM and VR represents a critical advancement in creating comprehensive cultural heritage experiences. While HBIM provides detailed 3D models that document the physical attributes of historical buildings, VR transforms these static representations into immersive environments that encourage exploration and interaction (Theodoropoulos & Antoniou, 2022). Users can virtually traverse archaeological sites and historic landmarks, engaging with spaces that may no longer exist. This integration facilitates the reconstruction of historical environments that have deteriorated or disappeared over time, offering visitors a unique journey through the ages (Poux, Valemboi, Mattes, Kobbel, & Billen, 2020).

On the other hand, early applications of VR in cultural heritage were often limited to basic visualisations or virtual walkthroughs of digitised environments. While these initial efforts were innovative, they provided a constrained view of VR's potential. However, as advancements in VR capabilities have emerged—such as sophisticated 3D modelling and improved user interfaces—the nature of these experiences has evolved dramatically (Lee, Kim & Choi, 2019).

Today, users actively engage with their surroundings, uncovering hidden details and deepening their understanding through real-time feedback in virtual environments. This interactive aspect enhances educational value and fosters a stronger emotional connection with historical narratives (Li, Ch'ng & Cobb, 2023). Virtual reconstructions of ancient structures, incorporating soundscapes and narrated histories, enrich the user experience (UX) (Soto-Martin, Fuentes-Porto & Martin-Gutierrez, 2020; Nabiev et al., 2019). VR transforms history from a static study to a dynamic, sensory experience.

Integrating VR with HBIM creates new research and public engagement opportunities in cultural heritage (El Barhoumi & Hajji, 2024). This combined approach allows scholars to analyse historical structures in previously unattainable ways, preserving and revitalising heritage (Xing, Xiao & Luo, 2024). It fosters educational outreach and public appreciation of cultural significance (Innocente et al., 2023; Taylor & Gibson, 2017).

The shift from static, professional environments to IVEs marks the rise of "Virtual Heritage" (Banfi, 2023; Huggett, 2020), offering experiences that make cultural landmarks and traditions accessible to wider audiences. VPL for XR development: towards XR cultural heritage experiences and virtual museums.

The International Council of Museums (ICOM) defines a virtual museum as "a digital entity that draws on the characteristics of a museum to complement, enhance, or augment the museum experience through personalisation, interactivity, and richness of content." Virtual museums can be centred around specific collections, like art or natural history, or feature online exhibitions from primary or secondary sources, as seen in science museums (ICOM, 2022). They may also serve as digital extensions of physical museums or represent born-digital content, including 3D objects, AR-VR, and digital art (Zuanni, 2021). Despite being grouped with other cultural institutions, virtual museums differ from libraries and archives. They are typically delivered electronically, also known as online, hyper, digital, cyber, or web museums (Taormina & Baraldi, 2023).

The European Union has funded various projects to support virtual museum development, including V-Must (Virtual Museum Transnational Network), which provides tools and resources for creating educational, engaging, and sustainable virtual museums (European Commission, 2024). Several notable initiatives have demonstrated the potential of virtual museums. The Louvre's VR experience "Mona Lisa: Beyond the Glass" allows users to explore the painting's details interactively (HTC Vive, 2019), while Tate Modern's VR offering lets visitors explore Modigliani's Paris studio (Tate Modern, 2017). The Natural History Museum's "Hold the World" VR experience, developed with Sky, allows users to interact with specimens and learn from Sir David Attenborough (Marie-Claire Eylott, 2017).

In archaeology, WebVR and QR codes have allowed visitors to discover tangible and intangible heritage, providing access to traditionally inaccessible areas (Banfi et al., 2024; Ramos Sánchez et al., 2022). Despite its advantages, virtual museums face challenges such as ensuring historical accuracy in digital reconstructions, addressing accessibility limitations due to high-tech requirements, and preserving digital heritage amid rapidly evolving technology. Schweibenz (2019) explored the role of virtual museums, noting that they do not replace physical museums but add a digital dimension to the museum experience, offering new opportunities for virtual communication.

In Italy, the pandemic significantly impacted the museum sector. An Istat report from 2020 showed that 63.6% of museums increased their social media presence and 46.1% improved their websites. Popular initiatives included virtual tours and online services like video interviews and live streams (Istat, 2022), though there were disparities in the digitisation of collections (Fig. 1).

Lombardia leads Italy in museum digitisation at 74%, followed by Lazio and Veneto. Abruzzo and Molise lag behind with 39% and 22%, respectively. Nationally, digital tool usage is under 50%, with video/screens (31%), QR codes/proximity systems (28%), and multimedia tools (22%) being the most common. Smartphone apps are used by 18%, and dedicated tablets by 8% (Fig. 2).

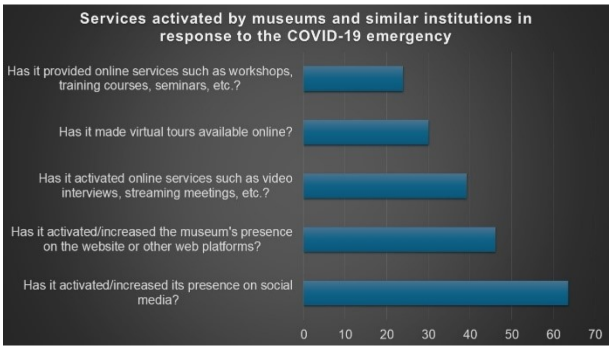


Figure 1. Services activated by museums and similar institutions in response to the COVID-19 emergency (source: Istat – Istituto Nazionale di Statistica, 2022).

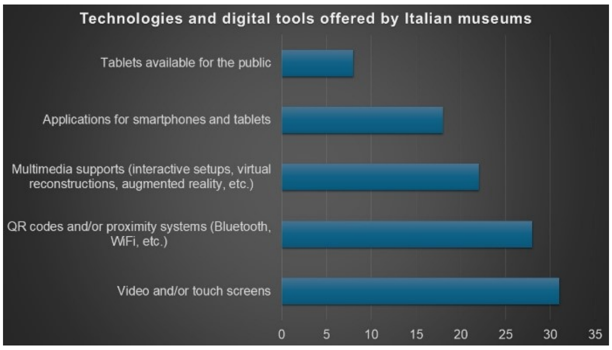


Figure 2. Technologies and digital tools offered by Italian museums (source: Istat – Istituto Nazionale di Statistica, 2022).

The Osservatorio Innovazione Digitale per la Cultura 2023 reports a 16% increase in visitors and a 27% rise in revenues for museums, monuments, and archaeological sites, surpassing pre-pandemic levels. Digital innovation is driving progress in many cultural institutions, with 54% of museums investing in visitor services and collection digitisation. 74% of museums have digitised part of their collection, and half have published digitised works online. Additionally, 29% offer augmented, virtual, and mixed-reality experiences, and 14% use generative AI for content creation in newsletters and social media (Fig. 3).

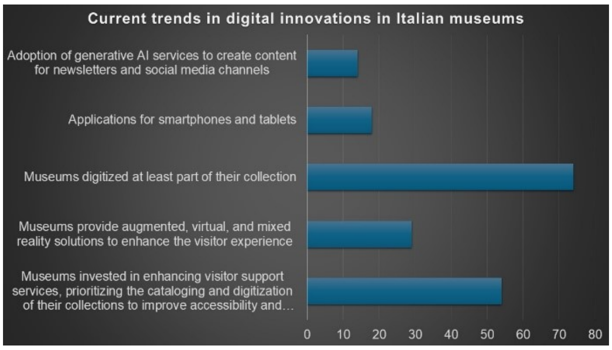


Figure 3. Current trends in digital innovation in Italian museums (source: Digital Innovation Observatory for Culture, 2023).

Building on this discussion, digital technologies, particularly VPLs, are crucial for creating immersive XR environments (Vohera et al., 2021). VPLs empower non-programmers to build applications using game engines like Unreal Engine, Unity, and Twinmotion, expanding possibilities for heritage conservation and virtual museums. VPLs, such as Scratch, LabVIEW, and Blockly, democratise software development, making it accessible to professionals in design, architecture, and cultural heritage (Pv, 2021). Popular VPLs such as Scratch, LabVIEW, and Blockly have demonstrated how visual programming can democratise software development, making it more accessible to individuals with limited technical backgrounds. This accessibility is particularly beneficial to design, architecture, and cultural heritage professionals, enabling them to actively contribute to creating IVEs with educational and interactive value.

In this context, various XR development platforms such as Unity, ARKit, ARCore, Vuforia, and Unreal Engine, can be employed (Jungherr, & Schlarb, 2022). The evolution of Unreal Engine, in particular, exemplifies the technological advancements within this space. Initially launched alongside the video game “Unreal”, the first version of Unreal Engine featured advanced capabilities, including high-quality rendering, collision detection, artificial intelligence, networking, and scripting, making it a comprehensive development tool. The engine’s custom scripting language, UnrealScript, was specifically created by Epic Games.

Over time, Unreal Engine has evolved into a widely-used platform for developing XR experiences. The release of Unreal Engine 4 in 2015, made freely available, accelerated the adoption and creation of IVEs worldwide. In 2020, Unreal Engine 5 introduced several groundbreaking innovations—Lumen, Nanite, and Taipei—further enhancing its technical capabilities. Officially launched in April 2022, Unreal Engine 5 enables professionals, filmmakers, and developers to manage complex models in real-time, thanks to its particle-based rendering system. This innovation streamlines the development process, allowing for the creation of detailed IVEs without extensive platform-specific optimisations.

Today, Unreal Engine supports multiple programming paradigms, including traditional C++ and visual scripting through its Blueprint system. Blueprint, a node-based visual scripting tool, allows users to design sophisticated game mechanics, animations, and interactions without writing code (Romero, & Sewell, 2019). Epic Games’ Twinmotion platform has also become a key tool for architectural visualisation, offering intuitive functionality for constructing virtual environments. This capability reduces development time and costs and enables the seamless integration of detailed scene elements, such as vegetation, characters, vehicles, and ambient sounds, enhancing the immersive quality of the environments. Twinmotion 2020.2 introduced features that allow for scene animation, such as opening doors when users approach, adding further layers of interaction and realism.

Looking at a broader trend in the products generated by these platforms, particularly in the world of gaming (Newzoo, 2024), the total number of players globally is predicted to increase by 4.5% next year, reaching 3.42 billion (almost half of the world’s population) (Fig. 4). Of this percentage, 3.9% consists of players who prefer PC gaming, translating to about 900 million additional players. Analysts estimate that this growth was facilitated by a robust release schedule 2023 that included highly praised cross-platform titles. On the other hand, the number of console players is growing slower, with an increase of only 2.3%. This figure is likely due to a relatively scarce content offering, which does not appear particularly appealing to this audience. In contrast, the mobile market is experiencing a growth rate of 3.5% and is expected to reach 2.85 billion by the end of 2024.

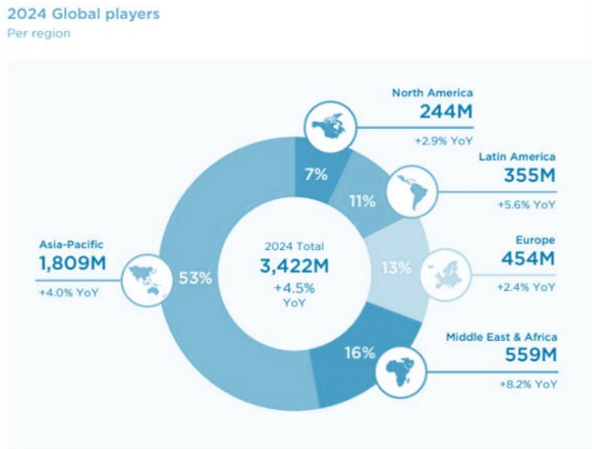


Figure 4. Global Game Market Report 2024. Global players per region (source: Newzoo, 2024).

Part of the growth in this segment is attributed to increased accessibility to smartphones in emerging markets and the corresponding spread of mobile networks.

In light of these advancements, the Ospedale Maggiore in Milan was an ideal case study for reinterpreting the relationship between 'content' and 'container' through a human-centric approach. A VR platform and a WebVR application have been developed here, enabling users to immerse themselves in an IVE enriched by interactive virtual objects (IVO), such as archival research, textual information, audio, and 3D animations.

At the heart of this study lies a bold ambition: to transform how people connect with and experience history. By harnessing the power of GEs and crafting interactive narratives, the study seeks to create compelling VR educational tools. This approach enhances the UX while supporting various devices, including desktops, VR headsets, tablets, and mobile phones.

3. Cultural and informative content: transparency, accessibility, sustainability and communication

When creating complex virtual models for the digital communication of cultural heritage, it is impossible to disregard the critical issue of information management linked to the content being conveyed, a foundational and pivotal aspect of any virtual storytelling project. This is particularly relevant considering the ease with which virtual objects can be modified and manipulated and the information they carry and represent. In this context, scientific rigour in the collection, selection, and transmission of information becomes an indispensable element in the design and execution of a virtual narrative concerning the history of a building, archaeological site, or historical artefact.

The "London Charter for the Computer Visualisation of Cultural Heritage" (Charter, 2009; Brusaporci & Trizio, 2013) underscores the need to establish, on an international scale, "a set of principles to ensure that digital heritage visualisation is, and is seen to be, at least as intellectually and technically rigorous as more established methods of cultural heritage research and communication." These methods must adhere to principles of intellectual integrity, reliability, documentation, sustainability, and accessibility. Such methodological rigour is essential, irrespective of the end-user type or the dissemination project's ultimate goal.

It is precisely the possibility of enabling an increasingly large and varied number of users to access cultural content conveyed through virtual, immersive and non-immersive digital models that lies the great potential of the digital, also responding to all those needs of sustainability and accessibility (also in connection with the issue of disabilities) that the scientific community nowadays poses as indispensable. It is in fact in the final document of the 19th ICOMOS General Assembly in New Delhi, December 2017, that the importance of these two aspects related to the fruition, material and non-material, of cultural heritage is reaffirmed: "sustainable means to work towards equity, ensure intellectual and physical access to heritage monuments and sites." The principles of information authenticity, virtual reconstructions, and scientific transparency are further clarified in the document "International Principles of Virtual Archaeology" (Lopez-Menchero & Grande, 2011). This work of graphic reconstruction must always be grounded in a thorough and systematic archaeological, architectural, and historical analysis. Such analyses should encompass a wide range of sources, including written, oral, and iconographic materials and photographic documentation. In the age of digital transformation, effective communication becomes the final and critical stage in this intricate process of transferring cultural content. This stage should leverage the most advanced technological tools available while recognising that these technologies are inherently evolving and, therefore, subject to obsolescence. As such, multimedia content must be developed with careful attention to the accuracy and quality of the cultural information presented and the usability and longevity of the media platforms themselves.

4. A research case study: the octagonal archaeological structures in the Filarete's courtyards of the ex-Ospedale Maggiore in Milan

Several factors drove the selection of this case study, foremost among them the availability of precise surveys of the buildings conducted through the integration of various methods and measurement instruments, ranging from laser scanning to photogrammetry and direct survey (Oreni, Karimi, & Barazzetti, 2017; Oreni & Fant, 2019). Furthermore, the case study was particularly suitable for constructing a virtual model capable of narrating the transformations of buildings with a well-documented history, both bibliographically and archivally.

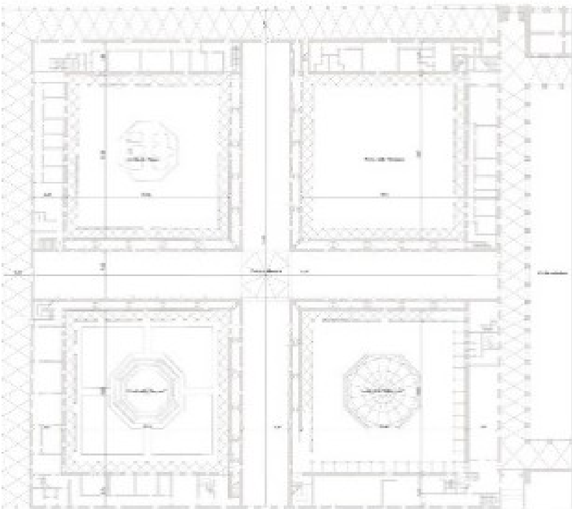
Numerous printed publications and scholarly articles exist on the Ca' Granda and its buildings (Pecchiai, 1927; Franchini, 1995), including the seminal works of Liliana Grassi (Grassi, 1958; Grassi, 1972), which were published following post-war restoration and reconstruction efforts. These texts, along with the works of historians and archaeologists, have overtime reconstructed the events and daily life associated with these spaces in the past (Vaglienti, 2014). This allowed testing the workflow developed and outlined in this paper on a real case, constructing a virtual product dense with established scientific content.

In particular, the choice was to deal with the three octagonal archaeological structures in the middle of three of the four 15th-century courtyards of Filarete (Fig. 5), which have never been 3D reconstructed in the past and are rarely involved in cultural enhancement projects.

These buildings are now considered of great value for the material history of the hospital but were considered in the past to be additions after the construction and not to be preserved. It was Ambrogio Annoni himself, architect and professor of Architectural Restoration at the Politecnico di Milano, who at the time of the restoration (1939) expressed his disappointment regarding "those small octagonal buildings that clutter the centre of the three courtyards of the icehouse, the woodshed and the baths for various uses". It is well known that they were not part of Filareti's project but had only been added later due to the hospital's changed functional needs. According to the restoration vision of that time, the new structures had interrupted the continuity of the open space that initially characterised the courtyards known as the 'Ice-house', 'Wood-shed' and 'Baths', thus representing a 'disturbing' element that had to be eliminated.

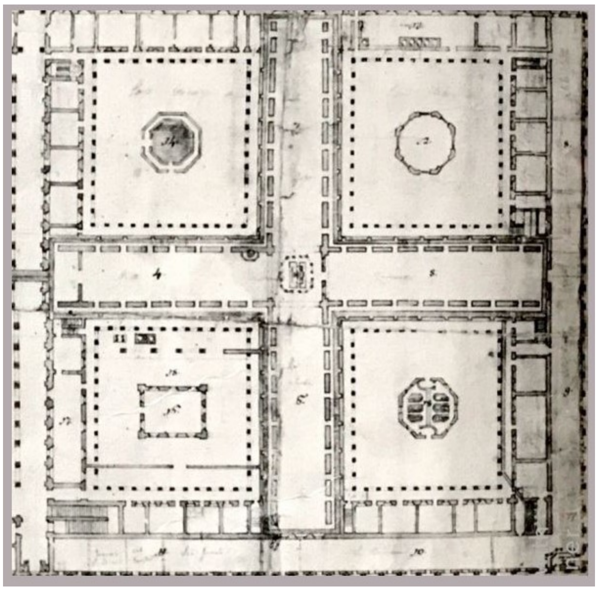
The presence of the oldest Icehouse and Woodsheed was first noted and graphically represented in the *Pianta del piano inferiore dello Spedal Maggiore di Milano* by the engineer Castelli in 1791 (Ospedale Maggiore Archives) (Fig. 6a), and then taken up again in the later *Pianta della Città di Milano degli Astronomi di Brera* of 1807 (Fig. 6b) and, in a more schematic manner, in the subsequent maps of the Catasto Lombardo Veneto of 1852-1856 (Milan State Archives). As far as the baths are concerned, it is the 20th-century plans that best describe the octagonal structure and the distribution of the internal tubs (Grassi, 1972) (Fig. 7).

(a)



(b)

Figure 5. Ospedale Maggiore in Milan: a) View of the four courtyards (source: Google); b) reworking of the floor plan from 3D survey data.



(a)

(b)

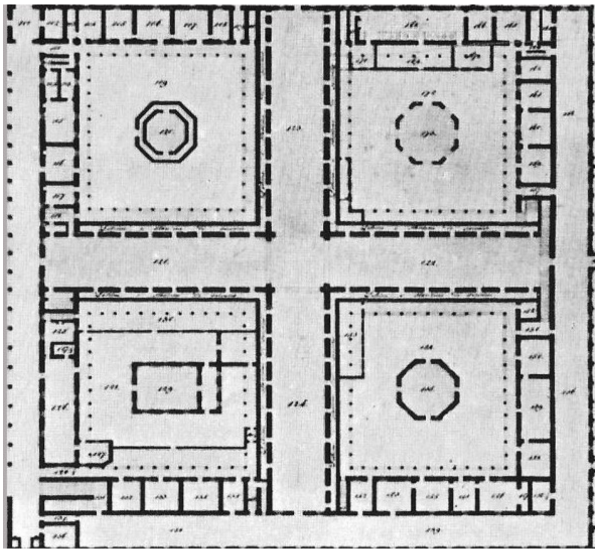
Figure 6. a) The floor plan of the lower level of the Ospedal Maggiore of Milan by engineer Castelli in 1791 in relation with b) the *Pianta della Città di Milano degli Astronomi di Brera* of 1807 (source: Ospedale Maggiore Archives).

Like most of the structures of the Ca' Granda, the three octagonal buildings were also extensively damaged and remodelled by the bombing in August 1943, with the collapse of the roofs and most of the above-ground walls. This situation prompted architect Liliana Grassi, who oversaw the restoration and reconstruction of the former hospital, to partially demolish the surviving structures up to ground level and then proceed with their complete covering with earth. The three structures were, therefore, concealed in the general rearrangement of the courtyards, and the situation remained as such until 1995 when archaeological excavations began that brought the three structures to light.

The three octagonal buildings are built precisely in the centre of the three courtyards of the same name and have similar planimetric dimensions, although they were inserted in different periods. Their length is approximately 1/3 of the overall size of the free space of each courtyard, and they substantially appear today as archaeological objects with no function other than that of being documents of themselves. Despite serving as the current headquarters of the *Università Statale di Milano* and attracting many students, researchers, and professors, the historical significance of these archaeological ruins remains relatively unexplored and underappreciated by visitors.

While guided group tours and descriptive totems provide limited insight into the courtyards' history, VR technology has considerable potential for cultural enrichment. Such an approach would allow for the development of virtual narratives highlighting the octagonal building's history. It should be emphasised that several initiatives of this kind have been carried out in recent years, including the creation of the 'VUMM - *Museo Virtuale d'Ateneo*' project (VUUM Virtual Unimi Museum, 2023), conceived, designed, realised and produced by the *Università Statale di Milano* precisely to make the history of four *filaretiana* courtyards known to the general public (Fig. 8).

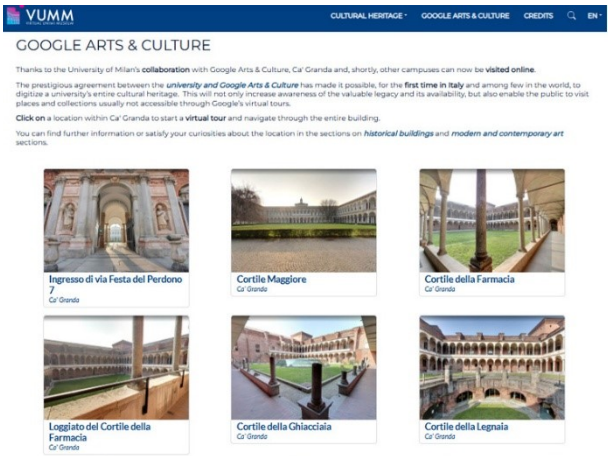
(a)



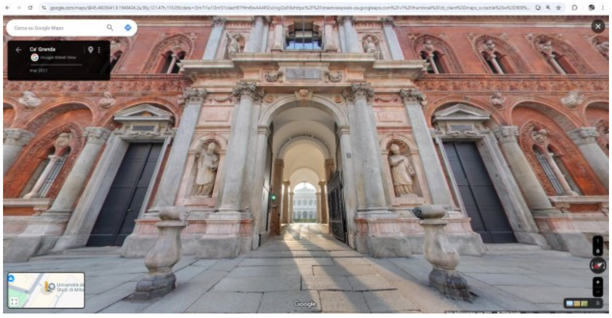
(b)

Figure 7. a) Maps of the *Catasto Lombardo Veneto* of 1852-1856 (source: Milan State Archives); b) 20th-century plans that best describe the octagonal structure and the distribution of the internal tubs (source: Grassi, 1972).

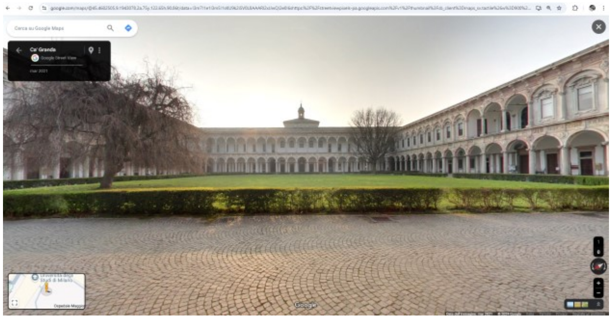
Through these instruments, research and initiatives can unlock the material and intellectual values accumulated within the building over the centuries, often accessible only to select experts. The oldest octagonal structure is the icehouse, built in the courtyard of the same name between 1636 and 1638. A resolution dated 29 November 1638 mentions the "*cella nivaria*" built to preserve food and medicines for hospital use, thanks to constipation inside the vaulted room of snow collected during the colder months. Inside the building, the circular cell was surrounded by an annular corridor with access stairs that served as insulation and as a storage room for products to be kept cool. Until the 1940s, the Icehouse's structure consisted of a sloping roof topped by a stone sculpture shaped like a pinecone, one of the Sforza symbols. Of the four courtyards, the war subjected the Icehouse courtyard to greater damage, with the significant loss of a large part of the building, as is well documented by the published photographs kept in the Grassi Archive at the Politecnico di Milano (Fig. 9).



(a)



(b)



(c)

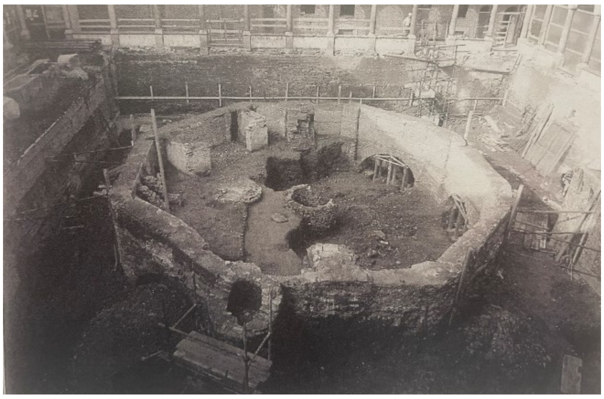
Figure 8.Virtual tours created with Google Street View for the "*Museo Virtuale d'Ateneo*" project allow users to experience a simulated visit through 360° panoramic images. a) The main menu provides access to various parts of the building, starting from b) the entrance at Via del Perdono 7 and leading to the c) main courtyard (Source: VUUM Virtual Unimi Museum, 2023).

For the first time, the structure of the Icehouse is graphically represented in the drawing by F. B. Werner, *Veduta della Ca' Granda* in 1740, engraving from the *Archivio dell'Ospedale Maggiore Ca' Granda Policlinico, Milan* (Fig. 10).

Unlike the courtyards of the "Pharmacy" and the "Baths," which Filarete built between the 1460s and 1470s, work on the Icehouse and "Woodshed" courtyard began in the 1480s. The Legnaia courtyard construction started in 1486, with Lombard workers partly following Filarete's design (Fig. 11). It was initially named the "Separate Women's Courtyard," then the "Courtyard of the Nizuola" due to a hazel tree.

(a)

(b)



(c)

Figure 9. a) View of the Icehouse today; b) after the bombings, and c) during the excavations of 1995 (source: Grassi Archive at the Politecnico di Milano).

Over time, after adding cooking rooms, it became known as the "Courtyard of the Kitchens" and later "Cortile della Legnaia." Archaeological findings from the 1990s revealed bread production, a henhouse, pigsty, and cattle stable in the late 15th century. By the 17th century, an octagonal building was constructed in the centre, likely due to space constraints at the hospital. Its original function is unclear, but by the late 18th century, it became a woodshed, serving that purpose until 1943 (Fig. 12).

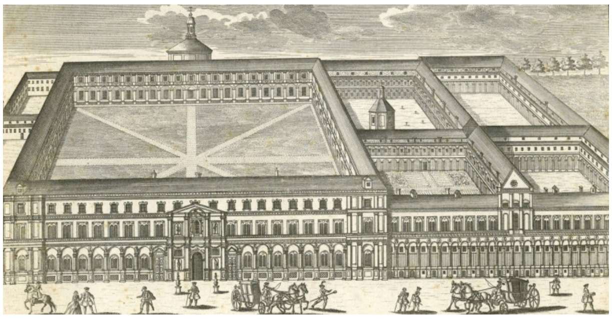


Figure 10. F. B. Werner, *Veduta della Ca' Granda nel 1740*, engraving from the *Archivio dell'Ospedale Maggiore Ca' Grande*, Milan.

Figure 11. View of the Woodshed today.

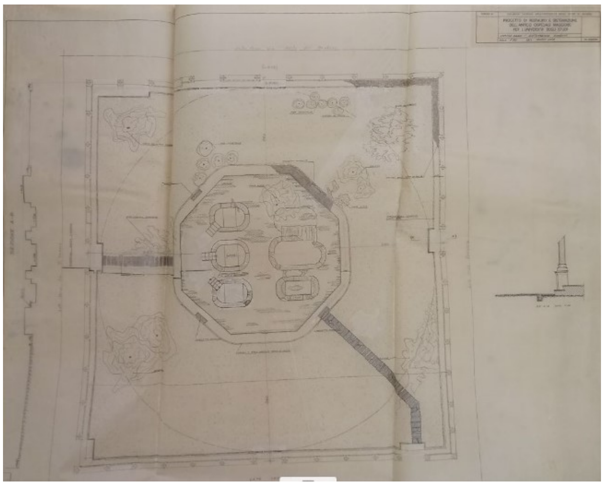
(a)

(b)

Figure 12. View of the Woodshed: a) before the bombing of the Second World War, and b) during the excavations of 1995 (source: Grassi Archive, Milan).

The Baths courtyard, built between 1467 and 1473, housed various patients, including noblemen, parturients, and those with isolating illnesses. In the 17th century, it became the nurses' space, called the "Servants Courtyard," with a cloakroom, laundry, and well-added, similar to the "Pharmacy courtyard." By the early 18th century, it was renamed the "Courtyard of the Baths" after tubs for partial immersion, known as semi-cupboards, were installed (Grassi, 1972). The octagonal structure was damaged in 1943, and its above-ground structures were dismantled in 1949 (Fig. 13).

(a)



(b)

Figure 13. View of the Baths: a) today, and b) the restoration project of 1974 (source: *Archivio Storico dell'Università degli Studi di Milano*).

5. The research method: Enhancing historical learning through VR and WebVR using HBIM and VPL

The following paragraphs describe how survey data, particularly the integration of the Baths and related archival research, were transformed into two distinct VR experiences. The first is a VR application designed for devices such as laptops, PCs, and VR headsets, aimed at providing a highly interactive and immersive solution to enhance the perception of the case study central to this research. The second experience, on the other hand, focuses on accessibility, targeting users who may not possess advanced skills or specialised devices. This latter experience, developed using WebVR technology, is optimised for touchscreen mobile devices, allowing users to easily access dynamic and interactive content via a simple QR code.

The common thread uniting these two VR solutions lies in a methodological framework that seeks to optimise the sustainability of generating HBIM from 3D survey data. Simultaneously, this approach fosters the development of immersive virtual environments (IVEs) and interactive virtual objects (IVOs), offering novel and experimental avenues for engaging with built heritage and its history within the broader domain of virtual heritage.

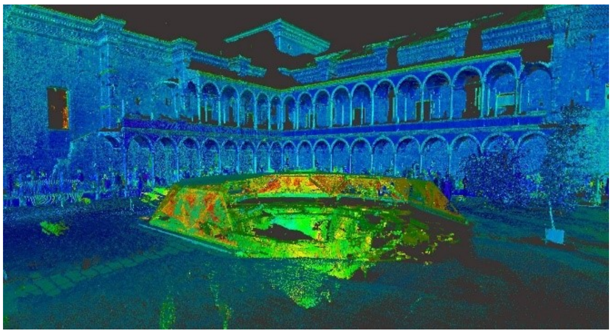
A comprehensive scan-to-BIM approach was employed to achieve this objective, integrating laser scans, topographic data, and primary photogrammetric outputs to produce detailed 3D models for VR development (VR app and WebVR). A key aspect of this approach is the parallel development of digital environments, which eliminates the need to open and close project files throughout the process repeatedly. By fostering a streamlined and cohesive workflow, the project team ensured the maintenance of graphical fidelity during the transition from traditional architectural drawing and modelling platforms—such as Autodesk AutoCAD, MC Neel Rhinoceros, and Autodesk Revit—to advanced XR development platforms like Twinmotion and Unreal Engine. The procedural framework, implemented from the 3D survey to VR deployment, highlights the refinement of critical steps to minimise time inefficiencies and enhance the visual accuracy of IVEs. This methodology preserves historical accuracy and improves the immersive quality of virtual reconstructions, making them accessible and engaging for both expert and non-expert audiences.

5.1. 3D model generation: from 3D survey to HBIM

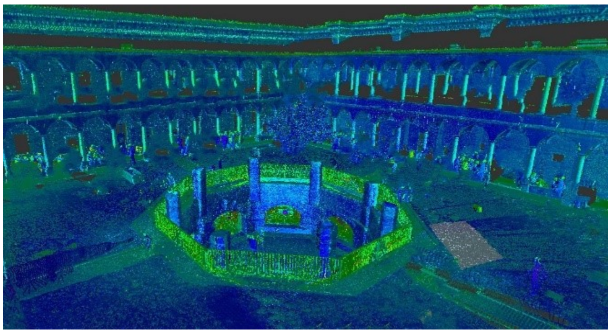
The acquisition of geometric and material data relied heavily on laser scanning and photogrammetry, with various instruments employed to meet the site's specific needs. For the 3D survey data integration of the courtyards, tools such as the Leica TPS1200, Faro Focus 3D X 130 HDR, and GeoSLAM Zeb were used to gather data from both ground level and the first floor of the loggias.

A geodetic network was established to integrate the terrestrial photogrammetry and laser scanning datasets into a cohesive reference system (Fig. 14). Measurements within this network, conducted using the Leica TPS1200 total station, achieved a precision of ±1.5 mm after a least-squares adjustment. This calibration produced a highly accurate point cloud, essential for synchronising data from the various instruments.

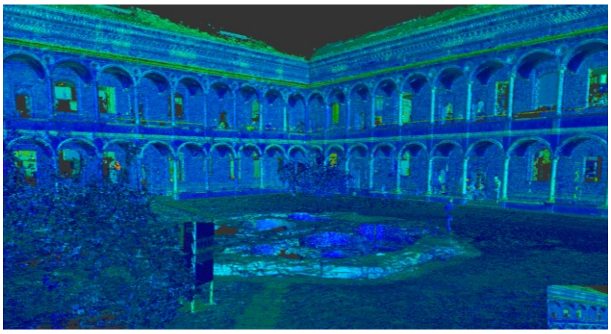
Additionally, a photogrammetric survey using Canon EOS 5D Mark IV and GoPro cameras captured detailed geometric and textured data for the IVE. The documentation process was divided into three phases: ground-level acquisition for detailed element documentation, upper courtyard surveys for ornamental façades, and first-floor loggia surveys for intricate architectural details (Fig. 15). Photogrammetry was crucial in reconstructing key architectural elements, such as vaults and columns, and creating a comprehensive digital archive. Printed targets optimised alignment accuracy, resulting in a georeferenced model with an alignment error of just 0.5 cm in Agisoft Metashape Professional Edition 2.2.0. software.



(a)



(b)



(c)

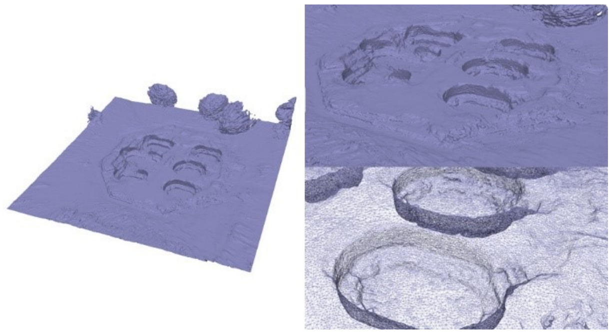
Figure 14. TLS data: a) Icehouse; b) woodshed; and c)Baths.

Initial outputs included high-precision 2D and 3D drawings of the facades, ceilings, and courtyards, facilitating a deeper understanding of the site's current condition and complex geometries.

These drawings enabled the semantic decomposition of point clouds, which were interpolated using Non-Uniform Rational B-Splines (NURBS) algorithms.

Both 2D and 3D outputs were obtained through the integration of a traditional redrawing approach, manually drawing on the point clouds themselves and using specific grades of generation (GOG 9 and 10, Banfi 2020; Banfi 2023) for the automatic generation of surfaces, and solids of complex elements such as irregular walls, arches and vaults. In both application processes, the interpretation of the starting data was fundamental in the points-to-drawings-to-models transformation process. Point clouds were managed in formats such as e.57 for 3D scanning data, .obj for high-resolution geometric models, and Autodesk's .rcp and .rcs for efficient integration into Autodesk AutoCAD 2024 and Revit 2024, streamlining the workflow and ensuring long-term sustainability of the data management process.

(a)



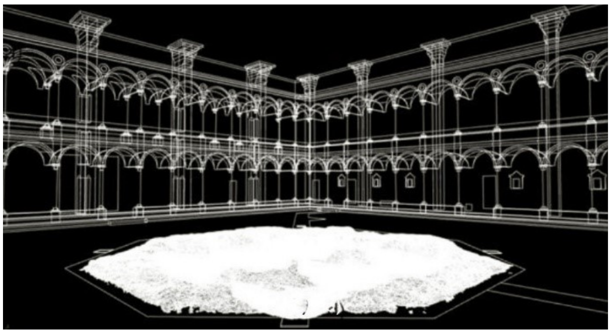
(b)

(c)

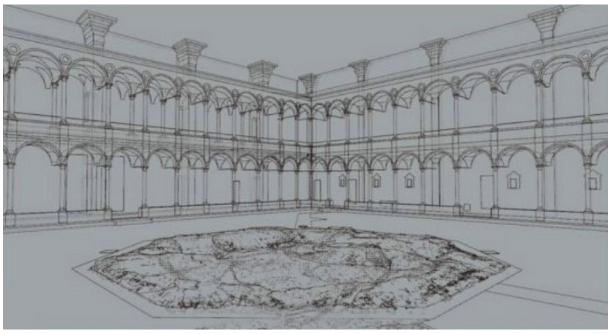
Figure 15. Photogrammetric data of the Baths: a) dense point clouds, b) mesh and (c) textured models.

Once the foundations for the generative process were established, NURBS modelling enabled the volumetric representation of the unique complexities associated with the courtyard's vaults, columns, capitals, and primary facades. This process transitioned from initial 3D drawings to surfaces and ultimately to solids, achieving a remarkable accuracy level (between the point cloud and modelled elements) of approximately 0.5 cm. Rhinoceros 8 was predominantly utilised due to its robust system features, including a fully integrated 2D drawing module and a 3D module, and its exceptional flexibility in managing a diverse array of forms—whether simple or complex—derived from photogrammetric point clouds and laser scans. The application of GOG 9 and 10 facilitated the direct interpolation of the points within the point clouds, ensuring an accurate representation of the current state (Fig. 16).

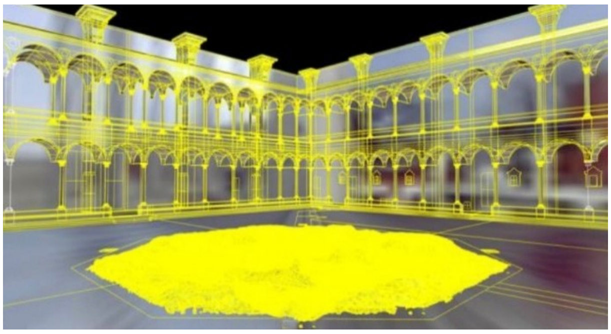
Banfi (2023) (p. 205) illustrates the .dwg export schema for Autodesk Revit 2024, which allowed for the precise extraction of 2D geometric entities, such as polylines and splines, as well as 3D entities like solids and NURBS surfaces.



(a)



(b)



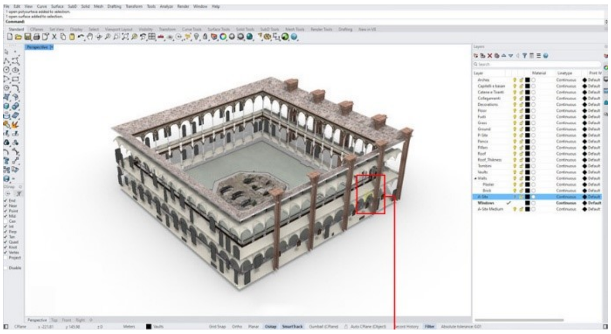
(c)

Figure 16. 3D Digital outputs from point clouds: from (a) 3D drawings and mesh model to NURBS model (b-c)

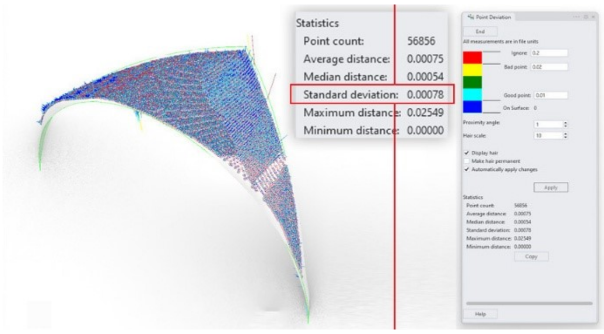
This step proved crucial for accurately transforming and recognising previously generated entities, thus enabling their automatic conversion into parametric BIM objects.

The BIM platform Autodesk Revit was selected for its superior compatibility with the .dwg format and its effective export schemes. It is considered more robust than competing platforms. Once the information mapping functions in Autodesk Revit were unlocked, the model's information system could be expanded by creating custom HBIM parameters, allowing for mapping historical phases, degradation pathologies, and more. In particular, the function 'Volumetrics and Construction/Site Mass/Insert/Import CAD' ensured that the geometric integrity of the model was maintained.

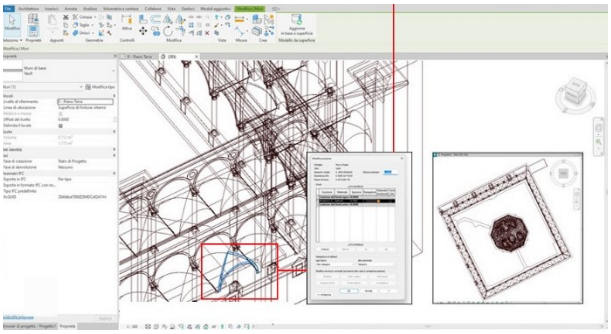
After defining the HBIM object type (such as materials and wall stratigraphy), the process moved on to the automatic or semi-automatic transformation of CAD/NURBS elements into BIM objects, linking them to alphanumeric information and HBIM parameters (Banfi, 2023, pp. 208-209) (Fig. 17).



(a)



(b)



(c)

Figure 17. Each NURBS geometric entity was converted into an HBIM object. Before conversion, the model's accuracy was assessed by automatically calculating the standard deviation between the generated model and the point cloud used.

This transformation is guided by 3D drawing and modelling rules, applying logical and practical frameworks that mirror the construction techniques used in the building. To minimise the use of a vast array of tools, formats, and software, the proposed research approach was structured around a straightforward workflow that utilised key output formats: laser scanner outputs (.las, .e57, .pts), photogrammetry outputs (.obj, .pts, .jpg, .png), AutoCAD and Recap Pro outputs (.dxf, .dwg, .rcs, .rcp), NURBS modelling outputs (.3dm, .dwg - 2007 solids schema, ACIS sat), and HBIM outputs (.rvt, .ifc, .excel, ODBC, .fbx).

Through this selection, 3D survey points were transformed into HBIM objects capable of communicating information in an open, standardised language that meets informational requirements. The .dwg format proved to be the most effective for interoperability between NURBS modellers and BIM software, provided that a specific export scheme was used to convert primitives, surfaces, and solids into BIM-compatible entities.

In line with the development of HBIM objects, additional fields were introduced to communicate the reliability of each component.

This included embedding the accuracy level of each element directly within the 3D model properties, along with textual information and links to external resources. The standard deviation of each object was displayed in the properties window, clearly defining the geometric and metric accuracy achieved and the resources used in the modelling process (e.g., TLS/photogrammetry point clouds, historical drawings).

At the same time, the in-depth analysis and understanding of the infographic materials obtained through archival research played a crucial role in supporting the interpretation, semantic decomposition, and 3D modeling phases. This process facilitated the identification of both historical and infographic data essential for the virtual narrative of the courtyards and the creation of informative 3D representations composed of sub-elements (granular HBIM objects), each characterized by an additional level of knowledge (Banfi, 2020).

Once the comprehensive HBIM model was finalised, it was disseminated through open and proprietary formats, including .ifc, .dwg, and .fbx, ensuring the effective transfer of information across diverse analytical frameworks and development stages. Extending beyond the conventional scan-to-BIM workflow, this study introduces a novel step incorporating innovative paradigms by integrating an interdisciplinary approach, further enhanced by advancements in VR development. This approach paves the way for new methodologies in the digital representation of cultural heritage, facilitating a more inclusive and immersive digital heritage experience.

5.2. Developing and evaluating the level of interaction in a VR project

The interaction methods between the user and the device in VR projects are paramount in ensuring an engaging and intuitive experience. These methods are influenced by various factors, including precise 3D modelling, format interoperability, VPL, the specific VR system in use and the project's unique requirements.

The transformation from static models to IVEs is profoundly shaped by the type of interaction intended for the end user. At this pivotal stage, where models and multimedia files converge with computer programming via VPL, defining a methodological approach that can consider, direct, and develop specific interaction modes becomes essential. Achieving an appropriate interactive and immersive experience depends on meticulously designed spatial and interactive logic grounded in sound digital proxemics.

If well-designed, the relationship between the user, the IVE, and the consumption device determines the level of interaction in the final product. To optimise this design, the present study has tested the most advanced interaction modes and devices, aiming to offer a comprehensive synthesis that engages both expert users and virtual tourists.

The development strategy pursued for the case study of the historical courtyards of the former *Ospedale Maggiore* in Milan involved the following interaction methods with an IVE. Regardless of the immersion level desired, these interactions can generally be categorised into the following primary types (Fig. 18):

a) *Controller-based Interaction Devices:* Devices such as Oculus Touch, PlayStation Move, and HTC Vive controllers provide a range of buttons, triggers, and motion sensors that enable users to manipulate objects, navigate interfaces, and interact with the virtual environment. These controllers offer tactile feedback and precise tracking, enhancing immersion.

b) *Gesture-based Interaction:* Advanced sensors and cameras track hand and finger movements, allowing users to interact with virtual objects without needing physical controllers. Some systems can interpret complex gestures such as pinching, grabbing, or swiping to perform specific actions, enabling more natural and intuitive interactions.

c) *Voice Interaction:* This method allows users to issue commands or communicate with virtual characters through speech. Supported by artificial intelligence systems such as Alexa or Google Assistant, voice interaction enhances the realism and accessibility of VR environments by enabling hands-free operation.

d) *Visual Interaction with Eye Tracking:* Eye-tracking technology lets users select objects or interact with the environment by simply gazing at them. Foveated rendering improves computational efficiency by rendering high-detail graphics only in the areas where the user is focused, reducing the processing load and improving performance.

e) *Physical Movement Systems:* Systems like omnidirectional treadmills or motion capture play areas enable users to walk or run in virtual reality. Position tracking via integrated sensors or external cameras monitors body movement in real time, adjusting the virtual environment to create a more realistic experience.

f) *Haptic Interaction*: Haptic feedback devices, such as gloves or suits, allow users to feel sensations like pressure, texture, or temperature of virtual objects. These devices can also provide physical resistance, simulating the experience of manipulating objects with weight or density, further enhancing immersion.

g) *Brain-Computer Interaction:* Although still experimental, brain-computer interfaces (BCIs) enable users to control virtual environments directly with their thoughts. BCIs interpret neural signals, allowing for more intuitive control and offering the potential for hands-free interaction.

h) *Social and Collaborative Interaction:* In social VR environments, particularly in multiplayer settings, users interact with others via customisable avatars. These interactions typically combine physical movement, voice communication, and gestures, enabling collaborative experiences and social engagement within virtual spaces.

These modes often combine to create immersive experiences that engage multiple senses and input methods, making VR more realistic and interactive. Therefore, defining the level or degree of interaction within a VR environment necessitates analysing various factors and determining the quality and complexity of the interaction between the user and the IVE. These factors can be classified based on interaction depth, environmental responsiveness, and user immersion.

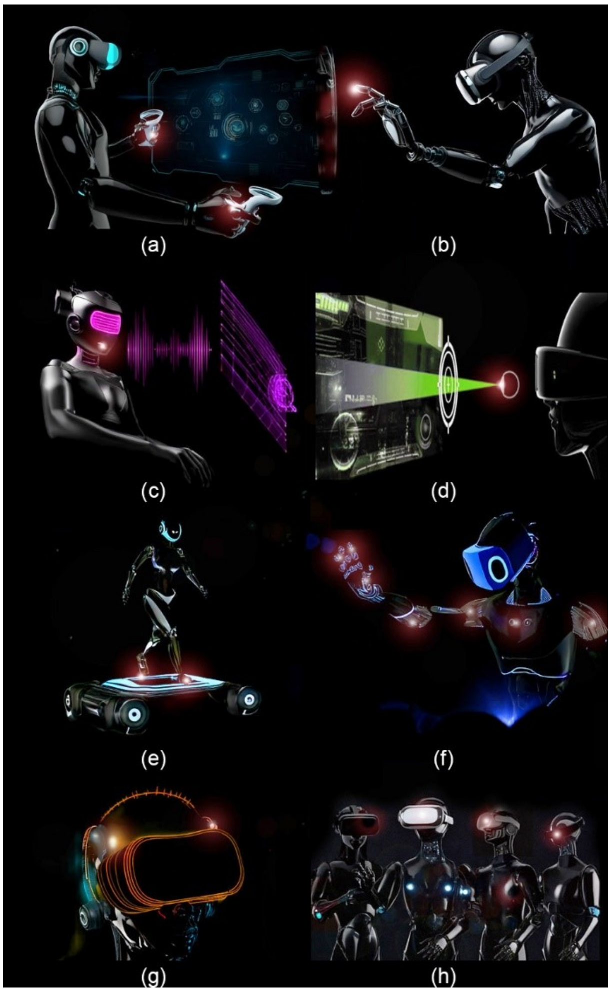


Figure 18. Primary tested interaction modalities in VR environments: a) Controller-based interaction; b) Gesture-based interaction; c) Voice interaction; d) Visual interaction (eye tracking); e) Physical movement; f) Haptic interaction; g) Brain-computer interaction; and h) Social and collaborative interaction.

The level of interaction in a VR project can be evaluated through various parameters that concern the quality and depth of interaction between the user and the virtual environment. Here are some of the main criteria for assessing interaction in a VR project:

1. Type of interaction:

a) *Passive interaction*: The user is merely an observer and does not interact actively with the virtual environment. This type of interaction is limited, but it can be helpful for experiences such as virtual tours or visualisations.

b) *Active interaction:* The user directly interacts with the virtual environment, manipulating objects, changing scenes, or influencing the system's behaviour. For example, the user might move through the environment, alter the visualisation, or select and manipulate objects.

2. *Sensory feedback:* Visual, auditory, and haptic feedback (if available) enhances interaction. A well-designed VR system provides immediate and consistent feedback regarding the user's actions. For example, vibrations or sounds accompanying an action can improve the interactive experience.

3. *Immersion:* The level of immersion refers to how much the user feels "inside" the virtual environment. The more a project creates a sense of presence and involvement, the higher the perceived level of interaction. Factors such as graphical quality, realism of environments, and accuracy of the simulation contribute to this aspect.

4. *Navigation and movement:* The ease and fluidity with which users can navigate the virtual environment are critical to interaction. The presence of an intuitive locomotion system (such as physical movement or teleportation) and the ability to freely explore contribute to a richer interactive experience.

5. *User control:* The level of control over actions and changes within the environment is a determining factor. If the user can directly influence objects or events in the environment (e.g., selecting, modifying, or moving objects), the VR project will have a higher level of interaction.

6. *User interface and usability:* The user interface (UI) design plays an important role in the accessibility and intuitiveness of the VR system. A well-designed interface that allows simple navigation and easy interaction with virtual elements contributes to effective interaction. Difficulties in use or interaction, such as a lack of clear instructions or complicated controls, reduce the quality of interaction.

7. *Social interaction:* In VR environments that support collaborative or multi-UXs, the ability to interact with other users or virtual entities is another key aspect. Real-time social interaction, such as communication or collaboration in shared scenarios, indicates a high level of interaction.

8. *Adaptability and personalisation:* The ability to adapt the experience according to the user's preferences or usage context, such as changing graphical settings, controls, or difficulty levels, can enhance interaction. Personalising the experience allows for individual needs to be met, making the interaction more engaging.

9. *Persistence and dynamic outcomes:* Another indicator of good interaction is the project's ability to adapt in real-time to the user’s actions, generating dynamic responses that affect the environment. The interaction feels more natural and engaging if the user's actions visibly and realistically alter the environment (e.g., moving objects, changing lighting, or the state of objects).

Several techniques can be employed to assess the level of interaction in a VR project. Direct observation involves monitoring how users engage with the virtual environment, closely analysing their movements, choices, and reactions as they navigate the experience. This method provides valuable insights into the user's behaviour and interaction patterns. Additionally, surveys and interviews allow for collecting qualitative feedback from users, offering a deeper understanding of their interactive experiences and any challenges they may encounter. Data analysis can further enrich the assessment by utilising tracking tools to gather quantitative data, such as the amount of time spent in specific areas, interactions with objects, or the frequency with which specific features are used. Lastly, usability testing is essential, involving test sessions with various users to identify potential problems or difficulties in interacting with the system. This iterative process helps refine the experience, ensuring it is intuitive, engaging, and effective for all users.

5.3. VPL for virtual heritage implementation: Enhancing the interaction and perception of architectural representation through a VR App

The inherent challenges associated with native 3D file formats posed significant obstacles to compatibility with XR development platforms, requiring a series of transformative processes to ensure seamless integration. The traditional workflow began by exporting the HBIM from Autodesk Revit, typically using formats like .fbx.

This format was specifically chosen for its ability to preserve crucial 3D geometry, textures, and relevant metadata, which are essential for GEs and real-time rendering environments. Performance optimisation was key to maintaining the model's integrity throughout the export process. This involved reducing polygon counts, adjusting texture resolutions, and eliminating unnecessary details that could affect rendering efficiency in real-time settings. Unreal Engine and Twinmotion, renowned for their advanced real-time rendering capabilities, played a pivotal role in creating detailed and IVEs, especially when paired with the Datasmith add-in.

This powerful plugin allowed for the seamless importation of 3D models and scenes from various design platforms, including Revit and Rhinoceros, while preserving the integrity of materials, geometry, and texture data.

Datasmith optimised scenes for real-time rendering by managing polygon counts and resource allocation while enabling collaborative workflows, automated scene creation, and material application, thus improving productivity and architectural visualisation quality. After optimisation, Unreal Engine's Blueprints system transformed static models into fully interactive IVOs and IVEs (Fig. 19).

Blueprints allowed the development of sophisticated user interactions without coding, enabling Virtual Visual Storytelling (VVS). This method guided users through virtual spaces, providing contextual information about the historical building and allowing interaction with IVOs, which featured architectural elements and enriched content like text, images, 3D animations, and audio, enhancing educational value.

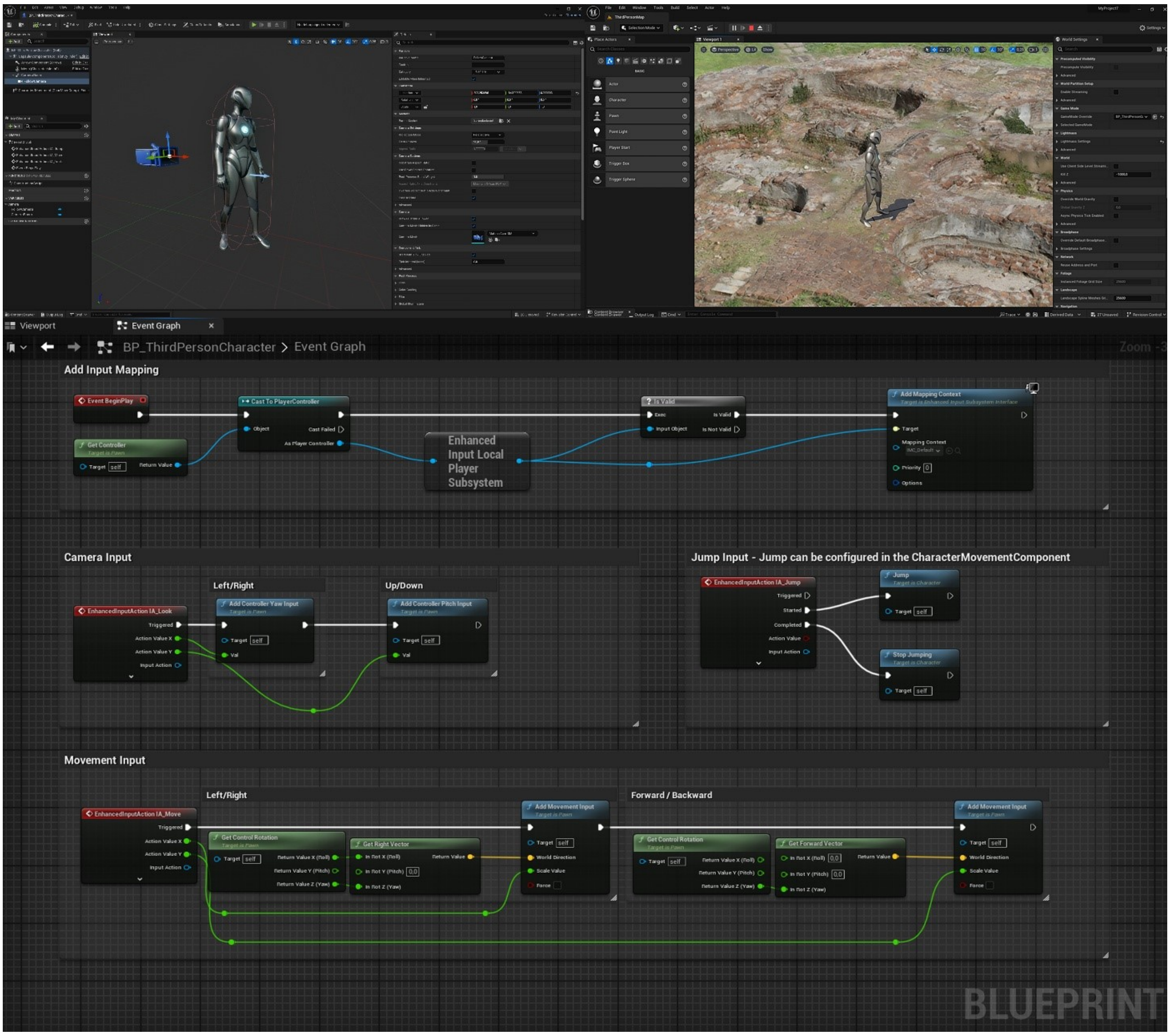


Figure 19. The main Blueprints developed to improve the interactivity of the third-person character for the VR app.

Blueprints enabled physics-based interactions within a third-person template in the VR application, including player controls like movement, jumping, object interaction, and a dynamic camera. This setup promoted user exploration, offering optimal viewpoints. Predefined animations and collision systems added realism to movement within the open-world setup. Using this third-person template, developers focused on complex game mechanics like VVS without starting from scratch.

Users interacted with IVOs by clicking, triggering pop-ups with historical context and audio narratives that guided them through the site, deepening their understanding of its cultural significance.

Blueprints also facilitated animated transitions and visual effects, enhancing immersion. As users approached features, dynamic lighting and ambient sounds activated, enriching the atmosphere. Additionally, users could seamlessly switch between third-person and first-person views by adjusting the camera, improving the experience based on user preference. This flexibility allowed users to interact with the space in third-person or engage directly through a VR headset in first-person mode without separate projects.

Finally, to package the VR application in Unreal Engine, the developer organised all assets and configured the project settings, previewing the application to identify and resolve any issues. The process began with configuring the software environment to support various VR devices, such as Meta Quest and HTC Vive. This involved enabling the necessary plugins within Unreal Engine and setting up the appropriate input configurations for VR controllers to ensure accurate user interactions within the virtual space. This step was essential for smooth control and seamless UX.

To optimise the project for performance, the developer reduced polygon counts in 3D meshes to minimise computational load while maintaining visual integrity. Texture compression was also applied to reduce file sizes and improve load times without sacrificing texture quality. Advanced techniques like foveated rendering were employed to improve performance by dynamically adjusting the resolution based on the user’s focus, enhancing performance and visual quality. Once the project was optimised, the packaging created an executable file, typically in .exe format for Windows. Unreal Engine processed all assets, converting them into formats compatible with the target VR platform. This ensured the application ran efficiently on specific hardware while maintaining high performance. After the build, the final output was tested on the target device to ensure smooth performance without latency or resource issues.

The development strategy aimed to maximise user interaction and immersion. The application featured an active interaction paradigm, allowing users to engage directly with the IVEs by manipulating virtual objects. To enhance the UX, multimedia elements such as video and audio were integrated into the IVE. High-detail HBIM with high-resolution textures (photogrammetric outputs) also contributed to hyperrealism, increasing the simulation’s fidelity. The VR application supported various devices for navigation, offering flexibility for users to customise their experience, whether navigating in first- or third-person view, as depicted in Fig. 20.

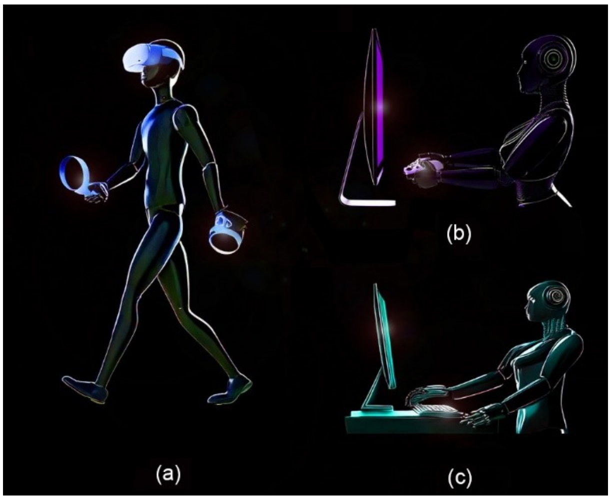


Figure 20. User interaction modes developed for the VR app: a) VR with 6 grades of freedom; b) interaction with PC desktop/laptop and controllers; c) interaction with PC desktop/laptop and keyboards.

Regarding point 6 (user interface and usability), the design approach utilised specific blueprints (Fig. 19) to leverage the advanced capabilities of the controllers integrated into the Meta Quest 3 headset, which features a new 4K+ display and dual RGB colour cameras that combine with a projector to deliver high-fidelity colour pass-through. The Touch Plus controllers were selected for their ergonomic button layout and sophisticated haptic technology, which provides more immersive and realistic tactile feedback.

The integration of Hybrid CV+AI tracking technology, TruTouch haptic feedback, and various input functions—including A/B/X/Y buttons, joysticks, capacitive touch thumb rests, a two-stage trigger, and precise finger closure movements—ensured a seamless and intuitive UX while minimising the learning curve associated with managing the controllers. To further enhance user mobility and provide advanced, unconstrained interaction within the IVE the blueprints were optimised to include six Degrees of Freedom (DoF) and a teleportation function through designated portal entrances and laser pointers (Fig. 21).

This innovation effectively overcomes the constraints of real-world physical space, allowing users to navigate freely within the IVE in an open-world format, independent of the physical size of the room. It eliminates concerns about spatial limitations or the need to traverse large distances, offering seamless, boundless UXs. Alternatively, for users who wish to reduce the DoF, a desktop solution is provided that does not require a VR headset or controllers. Using a PC or laptop with a keyboard or standard controller, users can engage in the UX from a third-person perspective, mimicking a traditional gaming setup while maintaining full interactivity.

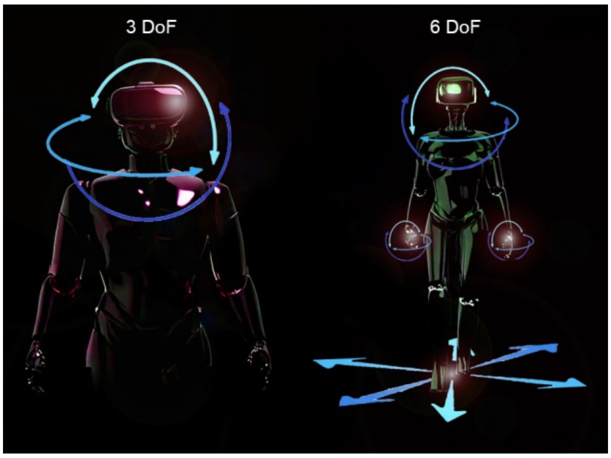


Figure 21. The VR app was developed to ensure 6 DoF, compared to traditional applications (3 DoF).

5.4. Enhancing built heritage accessibility with WebVR solutions.

In addition to a VR app offering a fully immersive experience, a second development track focused on new interaction paradigms. As briefly mentioned in the introductory sections, Unreal Engine is renowned for its graphical capabilities and ability to manage complex environments and advanced interactions. However, high-end hardware often requires dedicated VR headsets (e.g., Meta Quest, HTC Vive), specialised controllers, and powerful graphics-capable computers. These requirements can restrict the usability of UEs to a niche audience with access to such devices.

In contrast, Twinmotion provides a more accessible solution by supporting WebVR, enabling the creation of VR UXs that function directly within a web browser. This significantly simplifies access, as users are not required to install resource-intensive software or invest in expensive VR headsets. Anyone with an internet-connected computer or mobile device can engage with the UX using a simple link or QR code (Fig. 22).

This accessibility is particularly advantageous for heritage enhancement projects aiming to reach a broad global audience, including students, researchers, tourists, and general users without access to advanced technologies. While Unreal Engine offers a powerful, compelling, and flexible platform, it presents a significant learning curve. Developing VR projects in Unreal often involves complex programming languages like C++ or visual programming tools like Blueprints.

Although this level of complexity enables a high degree of customisation and interaction, not all content creators—particularly those in fields such as architecture, museums, or heritage conservation—possess the technical expertise required to leverage these capabilities fully. Another advantage of Twinmotion over Unreal Engine is its production efficiency. While Unreal Engine is designed to manage intricate, detailed environments with a high degree of interactivity, this often entails substantial investments of time and resources, including file management and performance optimisation. VR projects in Unreal Engine typically require manual optimisation of materials, textures, and polygon counts, which can significantly extend production timelines, particularly for teams with limited resources.

Figure 22. User interaction modes developed for the WebVR app.

Twinmotion's real-time rendering tools facilitate immediate visualisation of results, enhancing decision-making processes and enabling rapid revisions. This makes Twinmotion an excellent choice for projects with tight delivery schedules or developers seeking to iterate quickly on various project versions. Figure 23 illustrates how a specialised interface facilitates diverse interactions with various IVOs. The VVS has been meticulously designed to empower users with the freedom to navigate through multiple informational touchpoints.

Specifically, the narrative can begin at the main entrance of the courtyards, allowing users to proceed either clockwise or counterclockwise along the expansive portico on the ground floor. This design invites exploration of the archaeological sites at the centre, creating an engaging experience that can unfold in either direction.

Furthermore, users can engage with the content non-linearly, free from a predetermined sequence. The interface developed for the WebVR version and supplementary options allow users to interact with and perceive the IVE and IVOs in an open-world format. This flexibility extends to simulating atmospheric conditions, seasonal changes, and specific lighting effects, which users can adjust independently, enhancing the immersive and dynamic nature of the experience.

In particular, creating a WebVR application in Twinmotion offers a different methodology for enabling the visualisation of 3D models directly in a web browser, circumventing the need for specialised VR hardware. Twinmotion facilitates the importation of 3D models from other software such as SketchUp, Revit, or Rhino, allowing the enhancement of these models with lighting,

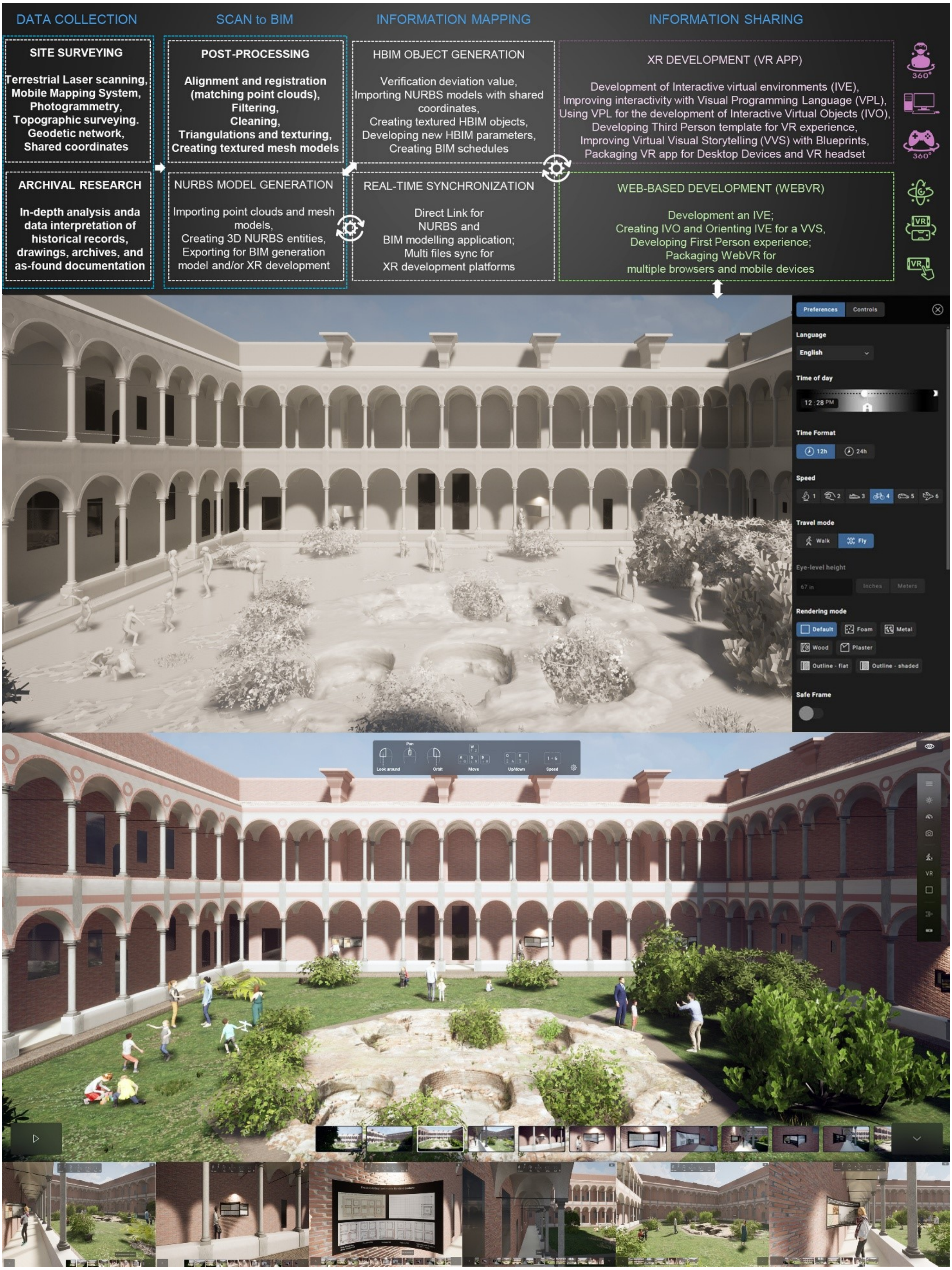


Figure 23. WebVR app includes interactive virtual objects that enhance the UX and incorporate historical information gathered during archival research.

textures, animations, and other details to create realistic, immersive environments. After finalising the model, the next step involves configuring the scene for WebVR export using Twinmotion's Presentation tool. This tool integrates interactive elements such as hotspots, allowing users to navigate the virtual environment while directly accessing supplementary information within the scene, such as text, images, or videos. Once the presentation is complete, the project is exported as a WebVR application, generating a set of files, including HTML, JavaScript, and optimised 3D assets tailored for web environments. These files can be uploaded to a web server, enabling users to access the immersive experience through a standard web browser. This approach allows the application to reach a broader audience, as it can be accessed on any device with WebVR compatibility, even without dedicated VR hardware, thereby extending the reach and accessibility of the immersive experience.

In addition to the WebVR implementation proposed in this study, the same IVE has been rigorously tested across desktop devices and VR headsets. Unlike the VR application developed in Unreal Engine, which confines users to a first-person perspective, this approach allows for richer engagement. By carefully developing varied content and establishing multiple access points, users can navigate in an open-world mode while seamlessly transitioning from one piece of content to another, akin to the experience of teleportation.

Crucially, establishing a specific VVS framework has proven instrumental in conveying the information gathered throughout the case study and its associated archival research in the most interactive manner possible.Whether engaging with the VR application or utilising the WebVR platform, users can uncover analyses, historical anecdotes, images, and descriptive texts related to the damage inflicted by World War II bombing. This immersive interaction fosters a deep connection to both the present and the past, transcending the limitations of reality and transporting users into a UX that holds the potential for further enhancement over time with additional content.

6. Results and discussion

Integrating detailed HBIM models with VR content significantly enhances the preservation of endangered sites by creating digital replicas that document their conservation status and cultural history. As technology advances, the shift from traditional HBIM to interactive VR experiences marks a crucial evolution in how historical sites are preserved and made accessible. This integration offers a new paradigm for heritage management that safeguards cultural memory and transforms how we engage with and experience our shared history.

Unreal Engine has proven effective in crafting immersive, high-quality VR experiences, often optimised for specialised hardware in museums and physical installations. However, this study advocates for a more inclusive approach that balances accessibility with visual fidelity. By leveraging WebVR through tools like Twinmotion, it is possible to create engaging cultural experiences accessible on devices as common as tablets and laptops, making them particularly valuable for educational purposes. While Twinmotion's real-time rendering capabilities may not match the level of detail achieved in Unreal Engine, its strength lies in offering dynamic environmental elements, such as changing weather and lighting, that provide a visually rich and interactive experience suitable for architectural and cultural visualisations.

Future advancements should focus on refining the workflows between HBIM and Twinmotion to enhance the synchronisation and retention of historical data in VR environments. Additionally, AR and XR technologies are expected to become key components of hybrid experiences that allow users to explore heritage sites virtually and in situ. WebVR performance optimisation will remain a priority, with future improvements in compression algorithms and distributed rendering techniques enabling the effective visualisation of complex 3D models. Features like real-time ray tracing in Unreal Engine may also make their way into WebVR, enhancing visual realism. Accessibility will remain a focal point, with assistive technologies and tailored interfaces set to ensure more inclusive virtual heritage experiences. Collaborative WebVR environments could also become the norm, allowing users to collectively explore and engage with cultural heritage sites, deepening interaction and understanding.

However, limitations, such as the lack of audio functionality in Twinmotion's Present Cloud, restrict the potential for immersive WebVR experiences. The inability to integrate customised audio content leaves WebVR experiences on mobile devices silent, starkly contrasting the richer, fully realised environments possible in Unreal Engine. This gap in functionality underscores the ongoing need for technological advancements, as outlined in Twinmotion's public roadmap (Epic Games Twinmotion Public Roadmap, 2024), which seeks to address these shortcomings. From a broader perspective, VR and WebVR offer transformative possibilities for museums—enhancing engagement, accessibility, and the interactivity of cultural experiences—but they also present challenges that require careful consideration. The immersive nature of these technologies deepens cognitive and emotional engagement, allows for dynamic learning experiences, and provides virtual access to historically significant objects and environments. However, the costs of development and maintenance and the need for continuous updates may be prohibitive for institutions with limited resources.

Additionally, not all visitors are familiar with VR technology or have access to the required devices, contributing to a potential digital divide. Furthermore, the solitary nature of VR experiences contrasts with the social interaction traditionally fostered by museum visits, potentially limiting collaborative learning opportunities. Finally, the quality of WebVR experiences heavily depends on internet connectivity, which could exclude users with less advanced technological infrastructure.While VR and WebVR represent significant opportunities to enhance museums' accessibility and interactivity, careful planning and consideration of the associated costs, technological requirements, and user inclusivity are essential for ensuring sustainable integration into cultural institutions.

7. Conclusion

The structure of this study, despite its inherent complexity, unfolds as a progressive exploration of the theoretical and practical foundations underpinning the digital representation of built heritage. Each section serves as a crucial milestone in understanding the evolution of a representational process increasingly intertwined with the technological challenges of the contemporary era. This discussion goes beyond a static analysis of the topics presented, highlighting the imperative for the continuous evolution of professional competencies required to adapt to a dynamic and shifting context. As Albert Einstein aptly stated, "Intelligence is the ability to adapt to change," a principle that emphasises the resilience now deemed essential for engaging with the novel paradigms dictated by technological advancement.

The study's first critical focus is analysing the historical context and principles of HBIM. Within this framework, drawing emerges as a representational tool and a communicative medium, bridging the gap between history, imagination, and materiality. The discussion extends further into the development phases of IVEs, illustrating how digital technologies have become indispensable for managing the increasing complexity of heritage conservation. The advent of HBIM represents a pivotal transition from static representation to integrated information management.

In this context, HBIM transcends its role as a mere technological tool, evolving into a shared language among professionals capable of streamlining decision-making processes and minimising errors. The core of the study delves into the future potential of immersive technologies, particularly the integration of HBIM, GEs, and XR environments. Here, developing a VR application and a WebVR platform marks a departure from the static nature of traditional technical drawings and 3D models, expanding into interactive and participatory dimensions. This innovative approach establishes a new paradigm, wherein end-users are no longer passive observers but active participants in the experience, fostering increased engagement and interaction. The analysis underscores a continuous dialectic between tradition and innovation, emphasising that the progression from HBIM to more advanced VR technologies represents not merely a technological evolution but a profound epistemological transformation in the communicative process.

Representation ceases to be static, evolving instead into an interactive and adaptive process that fosters connectivity among designers, clients, and end-users. In a technological landscape increasingly dominated by digitalisation, a multidisciplinary approach is indispensable—one in which technical expertise is seamlessly integrated with managerial, social, and cultural competencies. Only through a holistic framework incorporating these diverse domains will it be possible to fully leverage emerging technologies' potential while preserving the ethical and humanistic values at the heart of the architectural discipline.

References

Abbate, E., Invernizzi, S. & Spanò, A. (2022). HBIM parametric modelling from clouds to perform structural analyses based on finite elements: a case study on a parabolic concrete vault. *Applied Geomatics,* 14(S1), 79–96. https://doi.org/10.1007/s12518-020-00341-4

Adams, A., Feng, Y., Liu, J. C., & Stauffer, E. (2021). Potentials of Teaching, Learning, and Design with Virtual Reality: An Interdisciplinary Thematic Analysis. In *Educational communications and technology: issues and innovations* (pp. 173–186). Cham: Springer. https://doi.org/10.26803/ijlter.23.1.8

Alhakamy, A. (2024). Extended reality (XR) toward building immersive solutions: the key to unlocking industry 4.0. *ACM Computing Surveys*, 56(9), 1–38. https://doi.org/10.1145/3652595

Alizadehsalehi, S., Hadavi, A., & Huang, J. C. (2020). From BIM to extended reality in AEC industry. *Automation in Construction*, 116, 103254. https://doi.org/10.1016/j.autcon.2020.103254

Alizadehsalehi, S., Hadavi, A., & Huang, J. C. (2021). Assessment of AEC students' performance using BIM-into-VR. *Applied Sciences*, 11(7), 3225. https://doi.org/10.3390/app11073225

Andrade, A. (2015). Game engines: a survey. *EAI Endorsed Transactions on Game-Based Learning*, 2(6), 150615. http://dx.doi.org/10.4108/eai.5-11-2015.150615

Banfi, F. (2016). Building Information Modelling – a novel parametric modeling approach based on 3D surveys of historic architecture. In *Lecture notes in computer science* (pp. 116–127). Cham: Springer. https://doi.org/10.1007/978-3-319-48496-9_10

Banfi, F. (2020). HBIM, 3D drawing and virtual reality for archaeological sites and ancient ruins. *Virtual Archaeology Review*, 11(23), 16–33. https://doi.org/10.4995/var.2020.12416

Banfi, F. (2023). *Virtual Heritage| from 3D modelling to HBIM and extended reality.* Santarcangelo di Romagna (RN). Maggioli Editore.

Banfi, F., Dellù, E. R., Roncoroni, F., & Cacudi, G. (2024). Beyond digitisation and high-res 3D modelling of complex archaeological sites: shaping virtual heritage, XR engagement and preservation of Neanderthal Man's remains and Lamalunga cave. *Disegnarecon*, 17(32), 6-1. https://doi.org/ 10.20365/disegnarecon.32.2024.6

Barazzetti, L., Banfi, F., Brumana, R., Gusmeroli, G., Previtali, M., & Schiantarelli, G. (2015). Cloud-to-BIM-to-FEM: Structural simulation with accurate historic BIM from laser scans. *Simulation Modelling Practice and Theory*, 57, 71–87. http://dx.doi.org/10.1016%2Fj.simpat.2015.06.004

Barsanti, S. G., Giner, S. L., & Rossi, A. (2022). Digital Data and Semantic Simulation—The survey of the ruins of the Convent of the Paolotti (12th century A.D.). *Remote Sensing*, *14*(20), 5152. https://doi.org/10.3390/rs14205152

Bassier, M., Hadjidemetriou, G., Vergauwen, M., Van Roy, N., & Verstrynge, E. (2016). Implementation of Scan-to-BIM and FEM for the documentation and analysis of heritage timber roof structures. In *Lecture Notes in Computer Science* (pp. 79–90). https://doi.org/10.1007/978-3-319-48496-9_7

Bekele, M. K., Pierdicca, R., Frontoni, E., Malinverni, E. S., & Gain, J. (2018). A survey of augmented, virtual, and mixed reality for cultural heritage. *Journal on Computing and Cultural Heritage*, 11(2), 1–36. https://doi.org/10.1145/3145534

Bertocci, S., & Parrinello, S. (2015). *Digital survey and documentation of the archaeological and architectural sites*. UNESCO World Heritage List, Firenze, IT: Edifir.

Brumana, R., Della Torre, S., Previtali, M., Barazzetti, L., Cantini, L., Oreni, D., & Banfi, F. (2018). Generative HBIM modelling to embody complexity (LOD, LOG, LOA, LOI): surveying, preservation, site intervention—the Basilica di Collemaggio (L'Aquila). *Applied Geomatics*, 10(4), 545–567.https://doi.org/10.1007/s12518-018-0233-3

Brumana, R., Tucci, G., & Lerma García, J. L. (2019). Special Section Preface: Informative Models and Systems for Virtual Museum. *Virtual Archaeology Review*, 10(21). https://doi.org/10.4995/var.2019.12357

Bruno, Lagudi, Barbieri, Muzzupappa, Ritacco, Cozza, Peluso, Lupia & Cario, G. (2016). Virtual and augmented reality tools to improve the exploitation of underwater archaeological sites by diver and non-diver tourists. In *Lecture notes in computer science* (pp. 269–280). https://doi.org/10.1007/978-3-319-48496-9_22

Brusaporci, S., & Trizio, I. (2013). La" Carta di Londra" e il Patrimonio Architettonico: riflessioni circa una possibile implementazione. *SCIRES-IT-SCIentific RESearch and Information Technology*, 3(2), 55-68. http://dx.doi.org/10.2423/i22394303v3n2p55

Brusaporci, S., Maiezza, P., & Tata, A. (2018). A framework for architectural heritage HBIM semantization and development. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 42, 179-184. https://doi.org/10.5194/isprs-archives-XLII-2-179-2018

Buragohain, D., Meng, Y., Deng, C., Li, Q., & Chaudhary, S. (2024). Digitalizing cultural heritage through metaverse applications: challenges, opportunities, and strategies. *Heritage Science*, 12(1). https://doi.org/10.1186/s40494-024-01403-1

Calcerano, F., Thravalou, S., Martinelli, L., Alexandrou, K., Artopoulos, G., & Gigliarelli, E. (2024). Energy and environmental improvement of built heritage: HBIM simulation-based approach applied to nine Mediterranean case-studies. *Building Research & Information*, 52(1–2), 225–247. https://doi.org/10.1080/09613218.2023.2204417

Castellano-Román, M., & Pinto-Puerto, F. (2019). Dimensions and Levels of Knowledge in Heritage Building Information Modelling, HBIM: The model of the Charterhouse of Jerez (Cádiz, Spain). *Digital Applications in Archaeology and Cultural Heritage*, 14, e00110. https://doi.org/10.1016/j.daach.2019.e00110

Charter, L. (2009). *The London Charter for the computer-based visualisation of cultural heritage. Retrieved October 6, 2024*, from www.londoncharter.org

Chen, H. (2024). Comparative Analysis of Storytelling in Virtual Reality Games vs. Traditional Games. *Journal of Education Humanities and Social Sciences*, 30, 163–172.https://doi.org/10.54097/g1q95e20

Chow, L., Graham, K., Grunt, T., Gallant, M., Rafeiro, J., & Fai, S. (2019). The evolution of modelling practices on canada's parliament hill: an analysis of three significant heritage building information models (HBIM). *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 42, 419-426. https://doi.org/10.5194/isprs-archives-XLII-2-W11-419-2019

Coburn, J. Q., Freeman, I., & Salmon, J. L. (2017). A review of the capabilities of current low-cost virtual reality technology and its potential to enhance the design process. *Journal of computing and Information Science in Engineering*, 17(3), 031013. https://doi.org/10.1115/1.4036921

Cocchiarella, L. (2016). BIM: dimensions of space, thought, and education. *Disegnarecon*, 9(16), 3-1.

Conde, D., Balado, J., Soilán, M., Martínez, J., & Arias, P. (2023). LiDAR Data Processing for Digitization of the Castro of Santa Trega and Integration in Unreal Engine 5. *International Journal of Architectural Heritage*, 1-21. https://doi.org/10.1080/15583058.2023.2271877

Conti, A., Fiorini, L., Massaro, R., Santoni, C., & Tucci, G. (2020). HBIM for the preservation of a historic infrastructure: The Carlo III bridge of the Carolino Aqueduct. *Applied Geomatics*, 1-11. https://doi.org/10.1007/s12518-020-00335-2

Croce, V., Caroti, G., Piemonte, A., De Luca, L., & Véron, P. (2023). H-BIM and artificial intelligence: classification of architectural heritage for semi-automatic scan-to-BIM reconstruction. *Sensors*, 23(5), 2497. https://doi.org/10.3390/s23052497

Cruz, Y., Cabaleiro, M., Conde, B., Barros, B., & Riveiro, B. (2024). Methodology for the Integration of Structural Health Assessment of Masonry Bridges into HBIM. *International Journal of Architectural Heritage*, 1-23. https://doi.org/10.1080/15583058.2024.2342950

Di Biccari, C., Calcerano, F., D'Uffizi, F., Esposito, A., Campari, M., & Gigliarelli, E. (2022). Building information modeling and building performance simulation interoperability: State-of-the-art and trends in current literature. *Advanced Engineering Informatics*, 54, 101753. https://doi.org/10.1016/j.aei.2022.101753

Diara, F., & Rinaudo, F. (2020). Building archaeology documentation and analysis through open source HBIM solutions via NURBS modelling. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 43, 1381-1388. https://doi.org/10.5194/isprs-archives-XLIII-B2-2020-1381-2020

Dore, C., Murphy, M., McCarthy, S., Brechin, F., Casidy, C., & Dirix, E. (2015). Structural simulations and conservation analysis-historic building information model (HBIM). *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 40, 351-357. https://doi.org/10.5194/isprsarchives-XL-5-W4-351-2015

El Barhoumi, N., & Hajji, R. (2024). HBIM and Extended Reality for Cultural Mediation of Historical Heritage: A Review. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 48, 125-132. https://doi.org/10.5194/isprs-archives-XLVIII-4-W9-2024-125-2024

Epic Games Twinmotion Public Roadmap (2024). Retrieved October 6, 2024, from https://portal.productboard.com/epicgames/3-twinmotion-public-roadmap/tabs/4-under-consideration

European Commission (2024). Virtual Museum Transnational Network. Retrieved October 6, 2024, from https://cordis.europa.eu/project/id/270404

Fai, S., & Sydor, M. (2013, October). Building Information Modelling and the documentation of architectural heritage: Between the 'typical'and the 'specific'. In *2013 Digital Heritage International Congress (DigitalHeritage)*, 1, 731-734. IEEE. https://doi.org/10.1109/DigitalHeritage.2013.6743828

Fitria, T. N. (2023). Augmented reality (AR) and virtual reality (VR) technology in education: Media of teaching and learning: A review. *International Journal of Computer and Information System (IJCIS)*, 4(1), 14-25. https://doi.org/10.29040/ijcis.v4i1.102

Franchini, L., (1995). L'Ospedale maggiore di Milano dedicato all'Annunziata, detto Ca'Granda. *Ospedali lombardi del Quattrocento: fondazioney trasformazioni, restauri*, ed. by L. Franchini, Como, (pp.137-178).

Georgopoulos, A., & Stathopoulou, E. K. (2017). Data Acquisition for 3D Geometric Recording: State of the Art and Recent Innovations. In M. Vincent, V. López-Menchero Bendicho, M. Ioannides, T. Levy (Eds.), *Heritage and Archaeology in the Digital Age. Quantitative Methods in the Humanities and Social Sciences*. Cham: Springer. https://doi.org/10.1007/978-3-319-65370-9_1

Giordano, A. (2019). New Interoperable Tools to Communicate Knowledge of Historic Cities and Their Preservation and Innovation. In: Luigini, A. (Eds), *Proceedings of the 1st International and Interdisciplinary Conference on Digital Environments for Education, Arts and Heritage. EARTH 2018. Advances in Intelligent Systems and Computing*, vol 919. Springer, Cham. https://doi.org/10.1007/978-3-030-12240-9_5

Giordano, A., Russo, M., & Spallone, R. (Eds.). (2023). *Beyond Digital Representation: Advanced Experiences in AR and AI for Cultural Heritage and Innovative Design*. Springer Nature.

Gladstone, B. M., & Stasiulis, E. (2017). *Digital storytelling method. Handbook of research methods in health social sciences*, 1.

Gómez, A., Adineh, A., Rahrig, M., & Lerma, J. L. (2024). Narrating Serranos Bridge Evolution in Valencia (1500–2022) Using Historic Building Information Modelling and Historical Data. *Remote Sensing*, 16(2), 310. https://doi.org/10.3390/rs16020310

Grassi, L. (1958). *La Ca'Granda: storia e restauro*.

Grassi, L. (1972). *Lo'Spedale di poveri'del Filarete: storia e restauro*. Università degli Studi di Milano.

Grussenmeyer, P., Alby, E., Assali, P., Poitevin, V., Hullo, J. F., & Smigiel, E. (2011, June). Accurate documentation in cultural heritage by merging TLS and high-resolution photogrammetric data. In *Videometrics, range imaging, and applications X*I, 8085, (pp.79-91). SPIE.

Heesom, D., Boden, P., Hatfield, A., Rooble, S., Andrews, K., & Berwari, H. (2021). Developing a collaborative HBIM to integrate tangible and intangible cultural heritage. *International Journal of Building Pathology and Adaptation*, 39(1), 72-95.

HTC Vive (2019). Mona Lisa: Beyond the Glass at The Louvre I HTC VIVE ARTS. Retrieved October 6, 2024, from https://www.youtube.com/watch?v=Au_UpzhzHwk

Hu-Au, E., & Lee, J. J. (2017). Virtual reality in education: a tool for learning in the experience age. *International Journal of Innovation in Education*, 4(4), 215-226. https://doi.org/10.1504/IJIIE.2017.091481

Huggett, J. (2020). Virtually real or really virtual: Towards a heritage metaverse. *Studies in digital heritage*, 4(1), 1-15. https://doi.org/10.14434/sdh.v4i1.26218

ICOM International Council of Museums (2022). Museum Definition. Retrieved October 6, 2024, from https://icom.museum/en/resources/standards-guidelines/museum-definition/

Innocente, C., Ulrich, L., Moos, S., & Vezzetti, E. (2023). A framework study on the use of immersive XR technologies in the cultural heritage domain. *Journal of Cultural Heritage*, 62, 268-283. https://doi.org/10.1016/j.culher.2023.06.001

Istat – Istituto Nazionale di Statistica (2022). Musei e istituzioni similari. Musei aperti ma visitatori in forte calo nell'anno della pandem.Retrieved October 6, 2024, from https://www.istat.it/comunicato-stampa/musei-e-istituzioni-similari-in-italia-anno-2020/

Jordan-Palomar, I., Tzortzopoulos, P., García-Valldecabres, J., & Pellicer, E. (2018). Protocol to manage heritage-building interventions using heritage building information modelling (HBIM). *Sustainability*, 10(4), 908. https://doi.org/10.3390/su10040908

Jungherr, A., & Schlarb, D. B. (2022). The extended reach of game engine companies: How companies like epic games and Unity technologies provide platforms for extended reality applications and the metaverse. *Social Media+ Society*, 8(2). https://doi.org/10.1177/20563051221107641

Lee, J., Kim, J., & Choi, J. Y. (2019). The adoption of virtual reality devices: The technology acceptance model integrating enjoyment, social interaction, and strength of the social ties. *Telematics and Informatics*, 39, 37-48. https://doi.org/10.1016/j.tele.2018.12.006

Lerma, J. L., Navarro, S., Cabrelles, M., & Villaverde, V. (2010). Terrestrial laser scanning and close range photogrammetry for 3D archaeological documentation: the Upper Palaeolithic Cave of Parpalló as a case study. *Journal of Archaeological Science*, 37(3), 499-507. https://doi.org/10.1016/j.jas.2009.10.011

Li, Y., Ch'ng, E., & Cobb, S. (2023). Factors influencing engagement in hybrid virtual and augmented reality. *ACM Transactions on Computer-Human Interaction*, 30(4), 1-27. https://doi.org/10.1145/3589952

Liu, J., Azhar, S., Willkens, D., & Li, B. (2023, April). Static terrestrial laser scanning (TLS) for heritage building information modeling (HBIM): a systematic review. *Virtual Worlds*, 2,(2), 90-114.

Liu, J., Sun, G., & Shidujaman, M. (2024, June). Integrating Virtual and Real: A Holistic Framework for Mixed Reality Interactive Design in Museum Exhibitions. In *International Conference on Human-Computer Interaction* (pp. 367-387). Cham: Springer Nature Switzerland. https://doi.org/10.3390/virtualworlds2020006

Lo Presti, N., Castellazzi, G., D'Altri, A. M., Bertani, G., de Miranda, S., Azenha, M., ... & Mazzotti, C. (2024). Streamlining FE and BIM Modeling for Historic Buildings with Point Cloud Transformation. *International Journal of Architectural Heritage*, 1-14. https://doi.org/10.1080/15583058.2024.2330942

Lo Turco, M., & Tomalini, A. (2021). Esperienze di Machine Learning per l'arricchimento informativo di modelli HBIM: il progetto DECAI-Machine Learning Experiences for Information Enrichment of HBIM Models: the DECAI Project. DN, 9, (pp.47-59). 2610-8755

Lopez-Menchero, V. M., & Grande, A. (2011). The principles of the Seville Charter. In *CIPA symposium proceedings*, 2011, (pp. 2-6).

Loup, G., George, S., Marfisi, I., & Serna, A. (2018). A visual programming tool to design mixed and virtual reality interactions. *International Journal of Virtual Reality*, 18(2), 19-29. https://doi.org/10.20870/IJVR.2018.18.2.2904

Lovell, L. J., Davies, R. J., & Hunt, D. V. (2023). The application of historic building information modelling (HBIM) to cultural heritage: a review. *Heritage*, 6(10), 6691-6717. https://doi.org/10.3390/heritage6100350

Lumini, A. (2023). L'HBIM per la fruizione virtuale interattiva del Patrimonio Architettonico e dei metadati informativi. Il caso studio della Scuola di Guerra Aerea di Firenze.

Maiezza, P., & Tata, A. (2021). Standard for geometric and informative reliabilities in HBIM models. *Disegnarecon*, 14(26), 15. https://doi.org/10.20365/disegnarecon.26.2021.15

Marie-Claire Eylott (2017). Museum to star in Sky VR experience with Sir David Attenborough. Retrieved October 6, 2024, from https://www.nhm.ac.uk/discover/news/2017/april/museum-to-star-in-sky-vr-experience-with-sir-david-attenborough.html

Martinelli, L., Calcerano, F., & Gigliarelli, E. (2022). Methodology for an HBIM workflow focused on the representation of construction systems of built heritage. *Journal of Cultural Heritage*, 55, 277-289. https://doi.org/10.1016/j.culher.2022.03.016

Moyano, J., Musicco, A., Nieto-Julián, J. E., & Domínguez-Morales, J. P. (2024). Geometric characterization and segmentation of historic buildings using classification algorithms and convolutional networks in HBIM. *Automation in Construction*, 167, 105728. https://doi.org/10.1016/j.autcon.2024.105728

Murphy, M., McGovern, E., & Pavia, S. (2009). Historic building information modelling (HBIM). *Structural Survey*, 27(4), 311-327. https://doi.org/10.1108/02630800910985108

Nabiev, A. S., Nurkusheva, L. T., Suleimenova, K. K., Sadvokasova, G. K., & Imanbaeva, Z. A. (2019). Virtual reconstruction of historical architectural monuments: methods and technologies. *International Journal of Innovative Technology and Exploring Engineering*, 8(10). http://doi.org/10.35940/ijitee.J9901.0881019

Nagy, G., & Ashraf, F. (2021). HBIM platform & smart sensing as a tool for monitoring and visualizing energy performance of heritage buildings. *Developments in the Built Environment*, 8, 100056. https://doi.org/10.1016/j.dibe.2021.100056

Newzoo, (2024). Global game market report 2024. Retrieved October 6, 2024 https://newzoo.com/resources/trend-reports/newzoos-global-games-market-report-2024-free-version

Nieto-Julián, J. E., Farratell, J., Bouzas Cavada, M., & Moyano, J. (2023). Collaborative workflow in an HBIM project for the restoration and conservation of cultural heritage. *International Journal of Architectural Heritage*, 17(11), 1813-1832. https://doi.org/10.1080/15583058.2022.2073294

Noghabaei, M., Heydarian, A., Balali, V., & Han, K. (2020). Trend analysis on adoption of virtual and augmented reality in the architecture, engineering, and construction industry. *Data*, 5(1), 26. https://doi.org/10.3390/data5010026

Oreni, D. (2023). Detect the differences: Cultural Heritage survey, documentation and interpretation for conservation activities. *Disegnarecon*, 16(31), 19-1. https://doi.org/10.20365/disegnarecon.31.2023.19

Oreni, D., & Fant, R. (2019). E per lo Signore mi fu comandato ch'io dovessi fare uno disegno a proporzione di questo sito, il quale era per un verso quattrocento braccia e pell'altro cento sessanta. In *Riflessioni. L'arte del disegno/il disegno dell'arte* (pp. 855-862). Gangemi Editore.

Oreni, D., Brumana, R., Della Torre, S., Banfi, F., Barazzetti, L., & Previtali, M. (2014). Survey turned into HBIM: the restoration and the work involved concerning the Basilica di Collemaggio after the earthquake (L'Aquila*). ISPRS annals of the photogrammetry, remote sensing and spatial information sciences*, 2(5), 267-273. https://doi.org/10.5194/isprsannals-II-5-267-2014

Oreni, D., Karimi, G., & Barazzetti, L. (2017). Applying bim to built heritage with complex shapes: The ice house of filarete's ospedale maggiore in milan, Italy. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 42(2W5), 553-560. https://doi.org/10.5194/isprs-archives-XLII-2-W5-553-2017

Osello, A. (2012). *Il futuro del disegno con il BIM per ingegneri e architetti, The future of Drawing with BIM for Engineers and Architects.* Palermo, Italy: D. Flaccovio.

Osservatorio Innovazione Digitale per la Cultura (2023). Osservatori.net Digital Innovation Politecnico di Milano. L'innovazione digitale nei msuei italiani nel 2023.Retrieved October 6, 2024, from https://www.ipresslive.it/it/ipress/comunicati/view/59011/

Pan, Z., Cheok, A. D., Yang, H., Zhu, J., & Shi, J. (2006). Virtual reality and mixed reality for virtual learning environments. *Computers & graphics*, 30(1), 20-28. https://doi.org/10.1016/j.cag.2005.10.004

Park, J., Kim, J., Lee, D., Jeong, K., Lee, J., Kim, H., & Hong, T. (2022). Deep learning–based automation of scan-to-BIM with modeling objects from occluded point clouds. *Journal of Management in Engineering*, 38(4), 04022025. https://doi.org/10.1061/(ASCE)ME.1943-5479.0001055

Pavan, A., Mirarchi, C., & Giani, M. (2017). *BIM: metodi e strumenti. Progettare, costruire e gestire nell'era digitale*. Tecniche.

Pecchiai, P. (1927). *L'Ospedale maggiore di Milano nella storia e nell'arte: con notizie documentate su le origini e su lo sviluppo della organizzazione spedaliera milanese dall'evo medio ai tempi nostri e con altri varii studi ed appunti di storia milanese e lombarda. Arti grafiche* Pizzi & Pizio.

Pepe, M., Costantino, D., & Restuccia Garofalo, A. (2020). An efficient pipeline to obtain 3D model for HBIM and structural analysis purposes from 3D point clouds. *Applied Sciences*, 10(4), 1235. https://doi.org/10.3390/app10041235

Perez, Y., Golparvar-Fard, M., & El-Rayes, K. (2021). Scan2BIM-NET: Deep learning method for segmentation of point clouds for scan-to-BIM. *Journal of Construction Engineering and Management*, 147(9), 04021107. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002132

Poux, F., Valembois, Q., Mattes, C., Kobbelt, L., & Billen, R. (2020). Initial user-centered design of a virtual reality heritage system: Applications for digital tourism. *Remote Sensing*, 12(16), 2583. https://doi.org/10.3390/rs12162583

Pv, S. (2021). *Beginning Unreal Engine 4 Blueprints Visual Scripting.* Berkeley, CA: Apress.

Quattrini, R., Malinverni, E. S., Clini, P., Nespeca, R., & Orlietti, E. (2015). From TLS to HBIM. High quality semantically-aware 3D modeling of complex architecture. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 40, 367-374. https://doi.org/10.5194/isprsarchives-XL-5-W4-367-2015

Quintero, M. S., Blake, B., & Eppich, R. (2007). Conservation of architectural heritage: The role of digital documentation tools: The need for appropriate teaching material. *International journal of architectural computing*, 5(2), 239-253. https://doi.org/10.1260/1478-0771.5.2.240

Ramos Sánchez, J. A., Cruz Franco, P. A., & Rueda Márquez de la Plata, A. (2022). Achieving Universal Accessibility through Remote Virtualization and Digitization of Complex Archaeological Features: A Graphic and Constructive Study of the Columbarios of Merida. *Remote Sensing*, 14(14), 3319. https://doi.org/10.3390/rs14143319

Remondino, F., & Rizzi, A. (2010). Reality-based 3D documentation of natural and cultural heritage sites—techniques, problems, and examples. *Applied Geomatics*, 2, 85-100. https://doi.org/10.1007/s12518-010-0025-x

Rocha, G., & Mateus, L. (2021). A survey of scan-to-BIM practices in the AEC industry—a quantitative analysis. *ISPRS International Journal of Geo-Information*, 10(8), 564. https://doi.org/10.3390/ijgi10080564

Rocha, G., Mateus, L., Fernández, J., & Ferreira, V. (2020). A scan-to-BIM methodology applied to heritage buildings. *Heritage*, 3(1), 47-67. https://doi.org/10.3390/heritage3010004

Rodriguez-Garcia, B., Guillen-Sanz, H., Checa, D., & Bustillo, A. (2024). A systematic review of virtual 3D reconstructions of Cultural Heritage in immersive Virtual Reality. *Multimedia Tools and Applications*, 1-51. https://doi.org/10.1007/s11042-024-18700-3

Rolin, R., Antaluca, E., Batoz, J. L., Lamarque, F., & Lejeune, M. (2019). From point cloud data to structural analysis through a geometrical hBIM-oriented model. *Journal on Computing and Cultural Heritage (JOCCH)*, 12(2), 1-26. https://doi.org/10.1145/3242901

Romero, M., & Sewell, B. (2019). *Blueprints visual scripting for Unreal engine: The faster way to build games using UE4 blueprints*. Packt Publishing Ltd.

Rossi, M., & Armellino, L. (2023). The Rethoric of Space Representation: From Drawing Heritage to Visual Computing. *Img journal*, (8), 202-225. https://doi.org/10.6092/issn.2724-2463/16260

Rubio-Tamayo, J. L., Gertrudix Barrio, M., & García García, F. (2017). Immersive environments and virtual reality: Systematic review and advances in communication, interaction and simulation. *Multimodal technologies and interaction*, 1(4), 21. https://doi.org/10.3390/mti1040021

Safikhani, S., Keller, S., Schweiger, G., & Pirker, J. (2022). Immersive virtual reality for extending the potential of building information modeling in architecture, engineering, and construction sector: systematic review. *International Journal of Digital Earth*, 15(1), 503-526. https://doi.org/10.1080/17538947.2022.2038291

Salerno, R. (2019). Digital technologies for “minor” cultural landscapes knowledge: Sharing values in heritage and tourism perspective. In *Geospatial intelligence: Concepts, methodologies, tools, and applications* (pp. 1645-1670). IGI Global.

Schweibenz, W. (2019). The virtual museum: an overview of its origins, concepts, and terminology. *The Museum Review*, 4(1), 1-29. http://creativecommons.org/licenses/by-nc-nd/2.0/de/

Scianna, A., Gaglio, G. F., & La Guardia, M. (2020). HBIM data management in historical and archaeological buildings. *Archeologia e Calcolatori*, (1). https://doi.org/10.19282/ac.31.1.2020.11

Sdegno, A. (2016). *Tra CAAD e BIM/Between CAD and BIM*. nuove.

Sidani, A., Dinis, F. M., Sanhudo, L., Duarte, J., Santos Baptista, J., Pocas Martins, J., & Soeiro, A. (2021). Recent tools and techniques of BIM-based virtual reality: A systematic review. *Archives of Computational Methods in Engineering*, 28(2), 449-462. https://doi.org/10.1007/s11831-019-09386-0

Soto-Martin, O., Fuentes-Porto, A., & Martin-Gutierrez, J. (2020). A digital reconstruction of a historical building and virtual reintegration of mural paintings to create an interactive and immersive experience in virtual reality. *Applied Sciences*, 10(2), 597. https://doi.org/10.3390/app10020597

Tang, S., Shelden, D. R., Eastman, C. M., Pishdad-Bozorgi, P., & Gao, X. (2019). A review of building information modeling (BIM) and the internet of things (IoT) devices integration: Present status and future trends. *Automation in construction*, 101, 127-139. https://doi.org/10.1016/j.autcon.2019.01.020

Taormina, F., & Baraldi, S. B. (2023). Museums and digital technology: a literature review on organizational issues. *Rethinking Culture and Creativity in the Digital Transformation*, (pp. 69-87).

Tate Modern (2017). Behind The Scenes. Modigliani VR. The Ochre Atelier. Retrieved October 6, 2024, from https://www.tate.org.uk/whats-on/tate-modern/modigliani/modigliani-vr-ochre-atelier

Taylor, J., & Gibson, L. K. (2017). Digitisation, digital interaction and social media: embedded barriers to democratic heritage. *International Journal of Heritage Studies*, 23(5), 408-420. https://doi.org/10.1080/13527258.2016.1171245

Theodoropoulos, A., & Antoniou, A. (2022). VR games in cultural heritage: A systematic review of the emerging fields of virtual reality and culture games. *Applied Sciences*, 12(17), 8476. https://doi.org/10.3390/app12178476

Trizio, I., & Savini, F. (2020, October). Archaeology of buildings and HBIM methodology: Integrated tools for documentation and knowledge management of architectural heritage. In *Proceedings of the IMEKO International Conference on Metrology for Archaeology and Cultural Heritage, MetroArchaeo* (pp. 84-89).

Trizio, I., Savini, F., Giannangeli, A., Boccabella, R., & Petrucci, G. (2019). The archaeological analysis of masonry for the restoration project in HBIM. T*he International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 42, (pp.715-722). https://doi.org/10.5194/isprs-archives-XLII-2-W9-715-2019

Ursini, A., Grazzini, A., Matrone, F., & Zerbinatti, M. (2022). From scan-to-BIM to a structural finite elements model of built heritage for dynamic simulation. *Automation in Construction*, 142, 104518. https://doi.org/10.1016/j.autcon.2022.104518

Vaglienti, F.(2014). La Ca'Granda dei Milanesi: itinerario interdisciplinare nel fulcro di una metropoli multiculturale.

Vohera, C., Chheda, H., Chouhan, D., Desai, A., & Jain, V. (2021, July). Game engine architecture and comparative study of different game engines. In *2021 12th International Conference on Computing Communication and Networking Technologies (ICCCNT)* (pp. 1-6). IEEE. https://doi.org/10.1109/ICCCNT51525.2021.9579618

VUUM Virtual Unimi Museum (2023). I quattrocenteschi cortili della Ca' Granda — Google Arts & Culture. Retrieved October 6, 2024, from https://museovirtuale.unimi.it/googlearts

Wen, J., & Gheisari, M. (2020). Using virtual International journal of environmental research and public health, 15reality to facilitate communication in the AEC domain: a systematic review. *Construction Innovation*, 20(3), 509-542. https://doi.org/10.1108/CI-11-2019-0122

Wu, S., Hou, L., & Zhang, G. (2021). Integrated application of BIM and eXtended reality technology: a review, classification and outlook. In *Proceedings of the 18th International Conference on Computing in Civil and Building Engineering: ICCCBE 2020* (pp. 1227-1236). Springer International Publishing. https://doi.org/10.1007/978-3-030-51295-8_86

Xing, Y., Xiao, Y., & Luo, Y. (2024). Integrating restoration and interactive exploration to enhance cultural heritage through VR storytelling. *Scientific Reports*, 14(1), 21194. https://doi.org/10.1038/s41598-024-72182-9

Yang, L. I., Huang, J., Feng, T. I. A. N., Hong-An, W. A. N. G., & Guo-Zhong, D. A. I. (2019). Gesture interaction in virtual reality. *Virtual Reality & Intelligent Hardware*, 1(1), 84-112. https://doi.org/10.3724/SP.J.2096-5796.2018.0006

Zhang, Y., Liu, H., Kang, S. C., & Al-Hussein, M. (2020). Virtual reality applications for the built environment: Research trends and opportunities. *Automation in Construction*, 118, 103311. https://doi.org/10.1016/j.autcon.2020.103311

Zuanni, C. (2021). Theorizing Born Digital Objects: Museums and Contemporary Materialities. *Museum & Society*, 19(2), 184-198). https://doi.org/10.29311/mas.v19i2.3790