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HBIM and Extended Reality for Cultural Mediation of Historical Heritage: a Review

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HBIM AND EXTENDED REALITY FOR CULTURAL MEDIATION OF HISTORICAL HERITAGE: A REVIEW

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KEY WORDS: Cultural Heritage (CH), Historic Building Information Modelling (HBIM), eXtended Reality (XR), Cultural Mediation, Integration Challenges

ABSTRACT:

In the realm of Cultural Heritage, emergent technologies such as HBIM (Historical Building Information Modeling) and Extended Reality (XR) are becoming instrumental in creating immersive Virtual Heritage experiences. A review of relevant literature indicates that these technologies have been utilized to build 3D HBIM models and highlight them on immersive platforms for purposes of cultural dissemination and promotion. Technological progress now accommodates the assimilation of historical data via HBIM methodology, which opens avenues for novel communication forms and the distribution of information through extended reality techniques. This, in turn, ensures cultural mediation and heritage site promotion. This study aims to present a comprehensive survey of research surrounding the application of HBIM in heritage site preservation and management. Moreover, this paper intends to provide an overview of the concepts and the role of XR within HBIM, in supporting the cultural mediation and promotion of historical heritage. This research further delineates a pathway for future endeavours concerning the integration of XR technologies within the policies of architectural and built heritage conservation and assessment.

1. INTRODUCTION

Embedded within the intricate fabric of societies, Cultural Heritage (CH) encapsulates the historical chronicles woven through ancient monuments, structures, and artifacts, embodying the collective essence of humanity's past. However, the intrinsic value of these cultural remnants often faces a waning appreciation, notably among younger generations (Buhalis & N. Karatay, 2022). To invigorate interest and engagement, researchers are earnestly delving into technological avenues. Amidst these explorations, the fusion of HBIM and the expansive immersive landscape of XR emerges as a promising frontier. HBIM meticulously digitizes and reconstructs historical structures, ensuring their preservation, while XR transcends the confines of reality, offering vast immersive experiences.

This convergence, known as HBIM-XR, stands as a pivotal realm within Cultural Heritage, not merely for educational or reconstructive purposes but as a transformative catalyst for enriched exhibitions and multifaceted objectives. XR's boundless potential envisions the amalgamation of virtual landscapes with Cultural Heritage, promising immersive engagement, interactive exploration, and a profound bridge between historical narratives and modern audiences. This innovative fusion reshapes cultural preservation, introducing a new paradigm for engaging with the past, forging connections across time, and redefining the landscape of cultural interaction.

The CH exists in digital forms that are both tangible and intangible (Meng Li et al. 2022). The tangible (material) heritage includes artefacts, buildings, structures, infrastructures, and archaeological sites connected to the natural environment and the raw materials from which they were made. While the intangible (immaterial) heritage includes various values related to representations, practices, historical memories, knowledge and expertise that communities have built, used, and passed down because of a complex and varied historical evolution (Dembedza et al. 2022). Consequently, the digital heritage (DH) includes a sizeable amount of data that need to be gathered using a variety of tools and techniques to ensure, on the one hand, effective management of the heritage, and on the other hand, recognize, and preserve its historical significance.

Digital heritage is established by digitally transforming or converting extant physical entities into 3D models via 3D acquisition techniques like photogrammetry and LiDAR (Light Detection And Ranging), succeeded by the application of diverse 3D modelling methodologies such as spline-based approaches, Non-Uniform Rational Splines (NURBS) algorithms, and HBIM. The latter, based on parametric 3D entities (Moyano et al., 2022), are storable in repositories and replicable in analogous 3D frameworks.

HBIM, as outlined in Murphy et al.'s study (2009), involves a reverse engineering tactic that employs scans of BIM components to generate a blueprint of historic building structures. Murphy et al.'s findings posit that conventional BIM systems are not expressly designed for precise modelling of existing structures, amplifying intricacies in modelling historic edifices when employing HBIM.

Nevertheless, despite the commendable virtues of HBIM, its implementation confronts multifaceted hurdles. Predominantly

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designed BIM systems lack the inherent framework for expeditiously constructing models of extant structures, thereby exacerbating complexities and elongating the temporal investment requisite for modelling these specific architectural entities when employing HBIM methodologies. Furthermore, the intricate nature of BIM software presents a formidable barrier for novices attempting to comprehend its operational intricacies (Banfi & Mandelli, 2021). Moreover, the seamless amalgamation of HBIM models into diverse visualization frameworks remains elusive, demanding supplementary plugins and nuanced integration methodologies.

Immersive technologies, including Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), widely adopted in contemporary entertainment sectors, represent a whole set of experiences known as "Extended Reality" or XR, which integrates real and virtual worlds. As evidence suggests, the significance of XR technologies in CH domain cannot be overlooked, with potential applications ranging from education to exhibition enhancement, exploration, reconstruction, and virtual museums (Fonnet et al., 2017; Banfi 2020, Blomvik, 2022). Importantly, XR in the sphere of HBIM can revitalize cultural tourism by enhancing community engagement through MR or VR tools. Recent advancements in XR platforms have enabled increased immersion into architectural and historical realms via VR and MR interfaces, facilitating an accurate representation of environmental details. Complementing their technological facilitation of visualization and display, HBIM-XR integration is increasingly acknowledged to extend their utility as a cultural mediation tool, fostering historical knowledge sharing, cultural enrichment, and interactive narrative schemes associated with specific historical periods. However, HBIM-XR integration brings some research questions mainly related to interoperability of their environments that should be addressed by researchers.

The present paper aims to provide a comprehensive review of the literature on the use of HBIM and XR for cultural heritage. Furthermore, it addresses the role of XR within HBIM in supporting multi-use, multi-platform cultural mediation and historical heritage promotion. This paper paves the way for future efforts to integrate XR technologies into cultural mediation strategies and historic site management by rising some technical challenges and proposing a research agenda to deal with them.

The research method relies on a scientific investigation beginning with a thorough review of articles relevant to the paper's key terms. The discussion then moves on to the roles of HBIM in CH and the integration of HBIM-XR in cultural mediation. Following a thorough examination of these aspects, the gathered information is synthesized for clarity and comprehension. The study concludes with a discussion that summarizes the findings, and future research directions. This review is structured as follows: Section 2 summarizes the current applications of HBIM and XR for cultural heritage modeling and mediation. Section 3 analyses the evolution progress of HBIM-XR integration. Section 4 discusses future trends and proposes potential opportunities of HBIM- XR integration. The paper ends with a conclusion in Section 5,.

2. BACKGROUND

2.1 HBIM for culture heritage modeling

In the recent years, there has been a growing interest in studying how to develop HBIM models (Historic BIM). Numerous studies highlight the usefulness of HBIM for documenting and recording information about heritage as the first phase in the life cycle of historic buildings. The results of research by Garcia-Valldecabres et al. (2016) have shown that this graphic and semantically unified information synchronized across all disciplines clearly improves management at later phases: intervention, execution, maintenance work and cultural mediation to society. All these phases pursue a single common goal, asset conservation.

In the continuum of digital modelling, BIM and its historical counterpart, HBIM, distinctly diverge across several critical dimensions. BIM predominantly caters to contemporary construction projects, facilitating collaborative virtual models for new developments. In contrast, HBIM serves as a specialized tool for the preservation and maintenance of historical structures, encapsulating their intrinsic attributes and cultural significance. While BIM captures comprehensive building data spanning design and construction phases, HBIM emphasizes information specific to historical edifices. Both aim for precise digital representations, with HBIM placing a heightened emphasis on geometric accuracy to preserve the unique architectural intricacies of historical constructions. Crucially, HBIM acts as a facilitator for conservation endeavours, offering a collaborative platform for stakeholders and seamlessly integrating conservation tasks within the model (Figure 1).

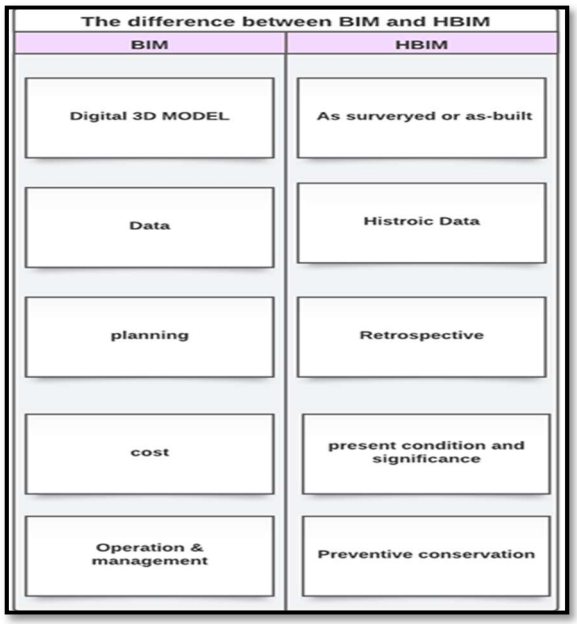

Figure 1: *In compared to traditional BIM data models, the figure illustrates the kind of information that should be incorporated in HBIM data models.(Yang et al. 2020)*

The HBIM process is a focused three-step procedure (Murphy et al. 2013; Bagnolo et al. 2019; Leon-Robles et al. 2019) (Figure 2). It initiates with data collection, where precise architectural and historical data about the building is gathered using photographic surveys, laser scanning, or manual measurements. Researchers and practitioners to capture geospatial data about heritage structures have embraced multiple innovative Reality Capture (RC) technologies. These techniques include Terrestrial Laser Scanning (TLS) (Alshawabkeh et al. 2021; Dore et murphy, 2017; Van Valkenburgh et al. 2020), photogrammetry, UAVs, and 360-degree photography among others. RC technologies accelerate data collection and reduce errors and deficiencies relative to the conventional method (Ibrahim, A et al. 2022; Banfi et al. 2019; Bastem et Cekmis , 2022).

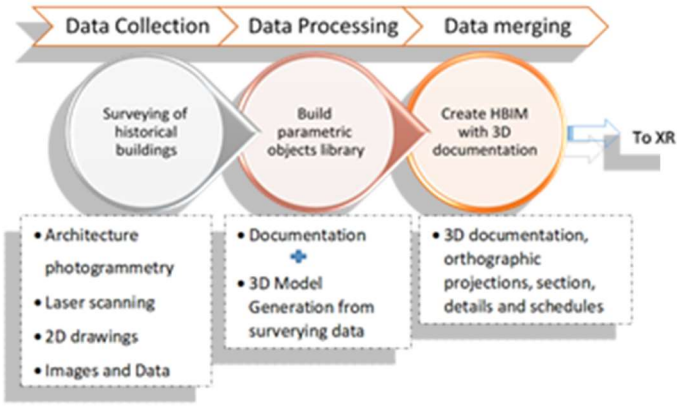

Figure 2: *Systematic overview of HBIM process*.

To surmount these hurdles, practitioners should devise meticulous TLS survey plans and integrate supplementary RC techniques (Junshan et al., 2023). Employing photogrammetry and Structure from Motion (SfM) as adjuncts offer cost-effective alternatives to TLS, albeit with potential precision trade-offs. SfM, particularly, excels in complex or confined settings where TLS might face limitations. Furthermore, the incorporation of UAVs with high-resolution cameras complements TLS by capturing aerial imagery, enhancing dataset comprehensiveness. Leveraging mobile scanning tools like handheld devices or mobile mapping systems amplifies agility, especially in inaccessible areas. This confluence of RC technologies alongside TLS, utilizing a multi-sensor integration paradigm, enables practitioners to optimize data precision and completeness in (HBIM) development.

Next, the collected data is processed—cleaned, segmented, and used to generate 3 D digital models. Finally, the data is merged: geometric and non-geometric data are combined to create a comprehensive, multidimensional model of the historic building. This result is the HBIM—a detailed representation that accurately captures the complexity of the historical structure. The entire process is iterative, involving constant review and refinement for accuracy.

In this regard, the creation of HBIM models requires the acquisition of highly accurate reality capture data, which may be obtained with traditional analogy tools (e.g., measuring tapes) and advanced instruments and techniques (Fobiri, 2021). Each of the techniques and technologies has its own advantages and limitations in the aspects of accessibility, comprehensiveness, level of accuracy, and feasibility.

In light of this, Banfi's research (2020) delineates a systematic approach aiming to enhance the integration of 3D data through the introduction of novel parameters, Grades of Generation (GOG), and Grades of Accuracy (GOA). This methodology focuses on the application of HBIM models within RV mediums, particularly emphasizing their augmentation for historical and archaeological sites. The study emphasizes the pivotal role of the 3D model's structure, underscoring its indispensable contribution to seamless integration into immersive platforms. The showcased case study stands as a robust demonstration of both the tangible and intangible significance of an archaeological site. Notably, immersive digital environments such as Virtual Reality (VR) and Augmented Reality (AR) emerge as promising avenues for transmitting historical heritage across generations and geographic boundaries, facilitating widespread digital dissemination over extended periods.

Transitioning to the examination of BIM's potential in heritage modelling, three distinct reviews contribute significantly to this field. Moyano et al. (2022) directed their focus on the intricacies of 3D modelling for heritage buildings, extensively analyzing the "as-built" BIM characterization from point cloud data, encompassing element morphology, interrelations, and attributes. Meanwhile, Cursi et al. (2022) provided a comprehensive summary of prevailing BIM platforms, particularly emphasizing the standardized HBIM procedures applicable to historical structures. Additionally, Bastem et Cekmis (2022) conducted an insightful review centred on the parametric modelling of heritage edifices within the BIM framework, highlighting the extensive potential of HBIM in the realms of cultural heritage conservation and management.

Recent studies on HBIM advancement have highlighted several potential real-world uses for the HBIM process during heritage conservation and valorisation of cultural projects. Cotella (2023) proposes a systematic review of on the advancement of HBIM and Artificial intelligence. The authors presented an overview of the uses of segmentation and classification of point clouds in the field of cultural heritage. Additionally, they stated that a variety of semi-automated geometrical BIM modelling tools have become apparent as a starting point for an artificial Intelligence (IA) investigation. The study brings a thorough analysis of the articles addressing IA applications for HBIM geometric reconstruction.

Meanwhile, Pepe et al. (2021) developed an innovative application utilizing HBIM and the Internet of Things (IoT) with the primary purpose of enhancing decision-making capabilities, environmental degradation prevention, and prediction of degradation of artefacts as a function of environmental conditions. Although promising, the researchers acknowledged several persistent challenges such as difficulties in managing extensive raw data from various sensors. They also pointed out an evident shortfall in novel operation methods, specifically relevant to structural appraisal and maintenance. The absence of

these novel methods limits the comprehensive simulation of structural performance under a multitude of actual or hypothetical situations. Building upon this, the authors propose the potential integration of such an approach into a numerical platform. They envision this platform comprising advanced tools and algorithms likely rooted in artificial intelligence or machine learning operations, hence optimizing the ability to handle and process complex, raw data.

In the domain of built heritage preservation and restoration, the emphasis on sustaining the integrity of historic edifices is a major area of focus (Glendinning, 2008). in this instance, Jouan et al. (2020) have made a significant contribution to this domain by proposing a methodical system aimed at enhancing conservation and restoration efforts. Central to their approach is the integration of HBIM in the conservation strategies (Fai et Rafeiro, 2014).

HBIM, a tool that offers comprehensive and detailed data about historic structures (Dore & Murphy, 2017), is proposed by Jouan et Hallot, (2019) to be combined with numerical logic equations. The utilization of these equations is intended to help in the formulation and enforcement of preventive strategies (Quattrini,Pierdicca, & Morbidoni, 2020).

Angjeliu et al. (2020) made important strides in examining the role of Digital Twins (DT) as a means of conserving architectural heritage, particularly from the perspective of structural safety. Their investigation emphasized that DT possesses the potential to proactively and in real time predict the structural status of historic buildings. This promising premise forms the basis of a DT system that utilizes precise simulation models and monitoring systems to generate these predictions. The authors argued that DT, through these systems, can serve as a dynamic, responsive tool that can span time and capture real-time changes precisely. This forms a live, constant, and accurate mirror of the physical world within a digital milieu, enabling architects and conservators to pre-emptively address structural concerns. Moreover, the detailed, specific modelling enabled by DT serves as a powerful predictive tool, permitting maintenance and safety efforts to be meaningfully targeted and phased.

2.2 HBIM XR Integration for cultural mediation

The term XR, originating in the 1960s, gained significance with computerized eyeglass-mediated reality in the 1990s and was further defined as "Cross Reality" in the early 2000s (Kjernisted, K., et McIntosh, D. 2007). Sony Corporation notably trademarked «XR» and «X-Reality», encompassing various technological aspects. XR serves as an inclusive category encompassing Augmented Reality (AR), Virtual Reality (VR), and Mixed Reality (MR), unifying these digital and physical realms enabled by technology and wearables.

Thanks to the recent advancements in digital technology, there has been a notable evolution in disseminating information about built heritage, manifesting in increasingly interactive and immersive forms within the domain of Digital Cultural Heritage (DCH). Studies in this field have generated virtual experiences embedding cultural, historical, and architectural significance. XR, notably AR and VR, has emerged as a pivotal force in fostering communication, engagement, and immersion among diverse user groups, ranging from construction specialists to students and virtual tourists (Ioannides et al., 2017). This progress has led museums and art galleries to offer virtual tours utilizing virtual reality headsets, web interfaces, panoramic tours, and gaming experiences.

Within the accuracy assessment of AR applications, researchers such as El Barhoumi et al. (2022) have honed in on refining precise placement to enhance user immersion. Their study identified technical limitations affecting model stability and placement accuracy, proposing a methodology to appraise key placement strategies focusing on precision and stability. Their comparative analysis encompassed marker-based and non-marker solutions, uncovering substantial placement errors in AR, particularly in marker-based systems influenced by marker quality, ambient lighting, marker-camera distance, and the sophistication of Software Development Kits (SDKs).

The XR platform allows users to examine the three-dimensional finishes of exposed faces. Historical documentation is gradually being integrated into HBIM, including references and links to tables in open-access collection libraries. Given its quantity of geometric and semantic data, this HBIM-XR integration has been incorporated into various use cases in the field of architectural heritage. This inventive synergy has also helped the field of cultural mediation, either directly or indirectly.

In French-speaking literature, the term 'mediation' is commonly utilized. It denotes an act of facilitating communication between differing entities, promoting an understanding or resolution (Bourdieu, 1991). On the other hand, the English-speaking literature often uses the term 'interpretation.' It refers to the process of explaining or giving meaning to something, usually a text or concept (Eco, 1995). While seemingly similar, these terms are underpinned by different philosophies and cultural connotations, emanating an essential dichotomy within translation studies itself. These points towards an inherent complexity in the universal understanding and application of such concepts across linguistic barriers (Seleskovitch, 1999). Further research would be required to trace the nuances and implications of these terms for a complete comprehension within both academic circles. Mediation is intrinsically multipurpose, involving communication, information, negotiation, reception, and education-oriented functions, and it is achieved through many mediums. Some researchers prefer to use the term mediation to represent all cultural practices that use media to bridge the gap between cultural elements and people (Lafortune, 2008).

XR applications, particularly Augmented Reality (AR), hold significant potential in fortifying cultural heritage by safeguarding its intrinsic values (Tiriteu & Vert, 2020). AR, renowned for its capacity to deliver personalized and immersive encounters, elevates visitor satisfaction within cultural domains (Perra et al., 2019). However, the examination of mobile AR

applications for cultural assets primarily leans on questionnaire-based assessments, neglecting comprehensive usability testing methodologies (Tiriteu et Vert, 2020). This highlights a critical gap, necessitating more sophisticated and multifaceted approaches to gauge the usability of such applications. Echoing this sentiment, the authors like Konstantakis & Caridakis (2020) underscore the urgency in formulating novel assessment criteria tailored for the evaluation of cultural heritage apps, emphasizing the need for a more comprehensive user experience analysis.

Ferretti et al. (2020) pioneered a semantically conscious HBIM model, integrating intelligent object parameterization alongside AR and digital content preservation techniques. This innovation serves the broader objective of preserving cultural heritage (CH). Notably, their study introduces two practical applications. Firstly, a MR application utilizing the Microsoft Hololens2 device simulates specific user experiences, focusing on museum management and thermo-hygrometric parameters. Additionally, a VR program for Oculus Quest offers interactive experiences such as narration and game interactivity, furthering the immersive potential for heritage engagement.

In a similar vein, Banfi et al. (2022) present a framework for integrating the most recent 3D modeling and digital survey techniques with the Visual Programming Language (VPL) and (XR) development platforms. The authors propose a scan-to-BIM-to-XR method based on various forms of architectural representation, digital survey (terrestrial and aerial). The building archaeology capable of transmitting the tangible and intangible values of various types of architectural artefacts, from large scale (building and its urban context) to medium scale (art collections, sculptures, museum itineraries) to small scale (building archaeology) of one of the most important historical buildings.

Building on these advancements, Zeng et al. (2022) proposed a pioneering mediation model introducing loyalty and individual collectivism to investigate the influence of VR's experiential value on tourists' cultural dissemination intentions. Their study aimed to analyze the impact of VR experiences, demonstrating that VR's experiential value significantly shapes tourists' intentions for cultural diffusion. This aligns with Dwivedi et al. (2020) research, focusing on VR's immersive capabilities, and Park et al.'s (2019) findings, both emphasizing VR's role in temporarily transcending reality. Moreover, McLean et al. (2023) highlighted VR's interactive nature, elucidating how it blurs virtual-physical boundaries, creating an environment fostering authenticity, entertainment, and pleasure. Collectively, these studies underscore VR's profound impact on shaping tourists' cultural dissemination behavior.

The study by Stanga et al. (2023) successfully integrated UAV photogrammetry, HBIM, and XR into a comprehensive survey strategy for a historical site. This innovative approach allowed for in-depth analysis of site structures, facilitating 3D modeling of stratigraphic units. Moreover, the application of HBIM and XR streamlined data interpretation, making it accessible to individuals without specific expertise. The project demonstrated the efficacy of three-dimensional reproductions in effectively communicating historical site aspects, emphasizing the potential of HBIM and XR integration for advancing heritage understanding and engagement (Stanga et al., 2023).

In contrast to conventional expectations, studies by Huang and Lo (2020) revealed an unexpected trend in Virtual Reality (VR) experiences, occasionally leading to decreased intentions of visiting actual locations (Huang & Lo, 2020). Despite these findings, the positive influence of VR cannot be disregarded. Research conducted by Chen and Wang (2018) demonstrated that individuals who perceive VR encounters as comprehensive and satisfying are more inclined to share their experiences, potentially stimulating heightened curiosity and interest in VR-based tourism among their peers (Chen & Wang, 2018). This complex interplay between VR interactions and physical tourism elucidates the need for further comprehensive studies to unravel the intricate dynamics.

The intricate relationship between VR experiences and their impact on real-world tourism is a multifaceted subject that requires careful examination (Huang & Lo, 2020). The dichotomy observed, where VR immersion may potentially deter physical visitation while concurrently stimulating interest through effective sharing of experiences, underscores the need for in-depth investigations. Such research, as highlighted by Chen and Wang (2018), would shed light on the diverse responses to immersive experiences and their subsequent influence on motivations for physical tourism.

2.3 SYNTHESIS

This synthesis serves as an amalgamation of profound insights extracted from a mosaic of studies exploring the fusion of HBIM and XR within the realm of cultural heritage. HBIM, meticulously designed for historical structures, functions as a digitized repository capturing multifaceted elements of cultural assets (Volpiano & Fabricio, 2019). The integration of Terrestrial Laser Scanning (TLS) and photogrammetry bolsters spatial coverage and precision, albeit challenged by environmental variables, necessitating astute Remote Sensing (RS) strategies for enhanced accuracy.

Going beyond conventional documentation, HBIM's impact extends deeply into heritage conservation and restoration endeavors. Its seamless integration into conservation methodologies and the nascent exploration of Digital Twins for predictive structural analysis delineate the versatile applications within this domain (Volpiano & Fabricio, 2019). Nonetheless, the efficient management of extensive raw data remains a pressing challenge, particularly in the seamless integration of HBIM with the Internet of Things (IoT), warranting specialized insights and innovative solutions.

The fusion of HBIM and XR heralds a transformative trajectory in cultural mediation, fostering immersive experiences and enriching communication within cultural heritage spheres. XR's potential in enabling three-dimensional reproductions signifies a promising avenue for conveying historical aspects and

enhancing audience engagement within the geospatial narrative of cultural heritage exploration.

3. DISCUSSION: CHALLENGES AND RESEARCH AGENDA

According to the scientific literature, the burgeoning field of HBIM and XR integration in cultural heritage mediation is proving to be increasingly significant. The semantic enrichment and interaction of these environments determine the experience and proximity created between the user and the content ensuring a bridge to multi-platform and multi-user cultural mediation (restaurateurs, architects, technologists and the public, among others.)

In our pursuit of seamlessly integrating HBIM and XR for historical sites, despite their promising benefits, we encounter persistent challenges. Technical complexities, like compatibility and interoperability issues, stand as barriers to overcome. Our strategic approach aims to address these challenges, offering insights into the intricacies of immersive technologies like AR and VR combined with HBIM. By bolstering our technical expertise, providing ongoing support, and refining our management skills, we can surmount these hurdles and foster a smooth integration of technology. This will enrich visitor experiences while preserving the historical integrity of these sites. Our forward-looking vision aligns with the innovative research by Banfi & al. (2021), aiming to introduce new method exchange formats and tackle interoperability challenges. Their exploration to make travel experiences more engaging and create novel interactions between users and virtual environments paves the way for new possibilities in the future of heritage sites.
As highlighted in the previous studies, HBIM-XR integration encounters challenges in data storage and management. The need for a centralized platform is evident, as HBIM falls short in addressing comprehensive heritage challenges. A major obstacle is the substantial volume of collected data, including tangible and intangible elements. Integrating this data requires considerations for social and cultural needs, demanding standardized archiving methods. The shift from 2D to 3D BIM management adds complexity. XR technologies in HBIM amplify challenges with increased data volume due to high-resolution assets, posing difficulties in effective storage and management.

Another concern is the overbearing data influx produced by HBIM, surpassing the capabilities of traditional databases. This problem intensifies when paired with XR applications which demand a high volume of data management. Adding to these challenges are the ineffective data structuring and standardization, causing inconsistencies in data storage and processing. The varied data formats in both HBIM and XR further complicate the issue, making it difficult to establish a unified platform for seamless data storage and retrieval. Furthermore, in integrating HBIM and XR, two key issues arise: data security and latency. Protecting sensitive information becomes complicated, and without safeguards, data breaches may occur. Besides, high data latency can impair real-time collaboration and immersive experiences, necessitating advancements in data processing, storage, and security for a successful HBIM-XR integration.

Furthermore, the challenges related to references and standards ensuring the quality of data acquisition and the structuring of geometric and semantic information, as well as metadata, are constant obstacles to achieving this HBIM-XR integration. Another significant issue is the high cost of technology. Indeed, developing and maintaining these technologies requires significant financial resources, which may limit their widespread adoption. Another issue is how to evaluate users' experiences with XR technologies based on their technological skills. Questionnaires were used to assess aesthetics, evasion (at the level of immersion), education, and entertainment. To address the aforementioned limitations, we identify the following research directions:

(i) *Interoperability:* The problem of interoperability is a major area of research in the field of HBIM-XR integration. This concern the absence of established protocols and procedures that would enable smooth communication between the different software platforms and tools used in XR and HBIM. The lack of established standards creates obstacles for effective cooperation and information sharing among these technologies. Future investigations into this area may examine and suggest standardized protocols and practices. In addition to bridging the gap between HBIM and XR tools, these standards would improve interoperability generally and guarantee a more seamless and integrated workflow. This could streamline information exchange across these interconnected domains, resulting in more effective heritage modelling, preservation, and immersive experiences.

(ii) *Storage and Database Management:* Given the large size and complexity of data contained in highly detailed 3D models, managing and storing, especially when needed in real-time in an XR environment, is perceived as an area that requires intense exploration. Future studies could develop innovative solutions for efficient and real-time data management. Precision and database types play key roles in the complex world of HBIM-XR integration. The accuracy of virtual models is directly impacted by precision, which is the degree of detail used to capture the tangible and intangible characteristics of heritage buildings. For HBIM and XR technologies to integrate with ease, this accuracy is necessary. In terms of database types, the structured methodology of relational databases makes it easier to manage related information, whereas semantic databases, with their emphasis on meaning and context, improve comprehension of cultural significance. In order to successfully integrate HBIM-XR, these databases must be carefully chosen and precisely implemented. This will guarantee accurate storage and retrieval of a wide range of heritage data.

(iii) Data structuring and standardization: many researchers that can be pursued to improve data standardization and structuring for HBIM-XR integration are numerous. Creating specialized ontologies with standardized terms and relationships based on heritage data is a critical area of focus. Investigating extensive metadata frameworks is necessary to ensure that historical data is consistently arranged and retrieved. It is critical to achieve semantic interoperability between XR and HBIM datasets in order to guarantee consistent understanding between different sources. Furthermore, the exploration of uniform data models

and standardized data exchange protocols can promote smooth communication amongst various software tools used in these fields. The development of strong and standardized practices is further aided by interdisciplinary cooperation, user-centered methodologies, and long-term data preservation techniques, which help to create a more coherent and interoperable environment for heritage information.

(iv) User Experience: Improving the HBIM-XR integration's user experience requires a multifaceted strategy that includes user-centered content, interactive features, immersive visualizations, and intuitive interface design. While guided learning paths make navigation easier, ensuring accessibility and gathering user feedback help with adaptability. The incorporation of gamification elements, performance optimization, and ongoing refinement based on user insights elevate the user experience and create a dynamic and engaging platform for interacting with heritage content. Compatibility across multiple platforms broadens accessibility.

In another section, the combination of HBIM and XR is very promising for increasing public participation in cultural heritage. To realize this potential, it is critical to develop effective procedural frameworks and employ digital communication tools. The successful implementation of these strategies could usher in a new era in cultural heritage preservation and communication, providing users around the world with an interactive and immersive historical encounter.

In this context, digital Twins (DT) can be deployed for a more authentic representation of the historical site. The final stage, Public Engagement, revolves around making the developed HBIM-XR model accessible, thereby promoting the site and bolstering conservation awareness. This stage underscores the importance of dissemination, lending further credence to the premise that accessible technology platforms are crucial for distributing HBIM-XR experiences. In the end, providing individuals with a user-friendly, interactive, and educational XR experience can create deeper connections with historical heritage. Concluding, the move from traditional methods of heritage documentation to a more interactive, digitized framework signifies a revolution in the conservation and promotion of cultural heritage. The strategy suggested ensures a structured development plan for HBIM-XR integration, facilitating historical site preservation while promoting widespread engagement. The incorporation of cutting-edge technologies such as XR, AI, and digital twin, within HBIM, marks the dawn of a new age in heritage preservation, fitting for the technologies of the 21st century.

4. CONCLUSION

The seamless integration of HBIM and XR in cultural heritage preservation denotes a shift in paradigm towards 'virtual cultural mediation'. This new approach combines accuracy with accessibility, allowing detailed virtual replication of CH objects for on-site or virtual exploration. Despite the existing challenges of disseminating cultural significance, especially to younger audiences, immersive experiences offer a solution by transcending geographical boundaries. The primary aim is to increase CH exposure among the public and encourage participation in its preservation. These innovative technologies can spark interest and shift public focus to historical sites by creating immersive, interactive, and educational experiences. The practicality of these applications will be validated in a realistic historical setting, while user engagement will be assessed and compared across XR and VR through interaction dynamics. This highlights the necessity for professionals to leverage these technological advancements to uphold the museum's cultural and societal role in the digital era.

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