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Enhancing HBIM-to-VR workflows: Semi-automatic generation of virtual heritage experiences using enriched IFC files

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ABSTRACT

In recent years, the digitization of Cultural Heritage (CH) has gained momentum, with Historical Building Information Modeling (HBIM) playing a vital role in developing services that enhance the understanding of built heritage. However, current HBIM-to-VR workflows, crucial for Virtual Heritage Experiences (VHEs), often rely on proprietary tools that may limit interoperability. To address this issue, some studies have used the Industry Foundation Classes (IFC) file format which, unfortunately, lacks functionalities for VHE creation, complicating the process for non-IT users. This paper introduces a semi-automated HBIM-to-VR workflow using an enriched IFC file. The process includes a manual phase for preparing the IFC file with metadata and a subsequent automated phase where a VR platform generates a virtual visit. A use case involving the "Hall of Seasons" in Palazzo Carignano, Turin, demonstrates the workflow's potential to improve accessibility and scalability in creating VHEs.

1. Introduction

With the advancements in technology and its related opportunities, it has become evident that the digitization of the built heritage can be key to make it gain even further value. This goal is often achieved through the use of Building Information Modelling (BIM), defined as "a digital representation of physical and functional characteristics of a facility" (National BIM Standard Project Committee et al., 2007). It basically serves as a shared knowledge repository for information about that facility, forming a reliable basis for decisions during its life-cycle from inception onward (National BIM Standard Project Committee et al., 2007). BIM was proposed for design purposes by Nederveen and Tolman in 1992 (van Nederveen and Tolman, 1992) but a widespread use was observed only starting from the 2010s (Lucchi, 2023). BIM-based processes encompass various types of data collected and stored during the construction process, aiming to create virtual information-based models to manage built artifacts in digital format (Alizadehsalehi et al., 2020). BIM tools are mainly used in the AEC (Architectural, Engineering, and Construction) industry but, in order to tailor them for heritage applications, the last decade has witnessed the introduction of Heritage BIM (HBIM) (Murphy et al., 2009). HBIM offers the typical advantages of BIM, adding the potential of interoperability, data storage and update, as well as the capability to cope with complex digital reconstructions of irregular geometries (Lucchi, 2023). Eventually, HBIM has become a *de facto* standard to preserve, enrich, and maximize the value of Cultural Heritage (CH) sites.

As the digitization of heritage through HBIM has evolved, so has done the exploration of immersive technologies in the considered domain, which can bring digital models to life. One of such technologies that received particular attention is Virtual Reality (VR), which enables the creation of interactive experiences (Alizadehsalehi et al., 2020). Within the field of CH, VR has been extensively explored to provide Virtual Heritage Experiences (VHEs). This term encompasses a wide range of virtual applications in CH, such as virtual tours and exhibitions, developed to enhance education (Paolanti et al., 2023), improve accessibility and inclusion (Selmanoviċ et al., 2020), and support heritage preservation (Skublewska-Paszkowska et al., 2022). VR-based VHEs share many characteristics with common commercial VR applications, offering a range of information visualization systems (Meinecke et al., 2022), such as User Interfaces (UIs) including text, image, and video panels, attention-guiding systems (Lu et al., 2021), and realistic 3D model representations within the VE (Chen et al., 2024). These experiences can be designed for stationary use (seated or standing) with the ability to look around (Jung et al., 2016), or they can leverage the room-scale capabilities of modern commercial VR systems, complemented by artificial locomotion methods such as continuous

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movement (Preloaded, 2021) and teleportation (Smithsonian American Art Museum, 2018; The Kremer Collection, 2017). Hand controllers also facilitate interaction with virtual elements, including UI components (e.g., buttons (Bayat et al., 2024)) and virtual objects related to CH contents (Spallone et al., 2024a). Additionally, audio descriptions, either pre-recorded (Louvre Museum, 2019) or generated in real-time through Text-To-Speech (TTS) (Bayat et al., 2024), are often provided to enhance adaptability and accessibility.

In some cases, to develop such VHEs the tools offered by BIM platforms are used (Wong et al., 2020). In most of the cases, however, general-purpose graphics engines like Unity or Unreal Engine, commonly exploited for creating games and other interactive experiences, are leveraged (Kamari et al., 2021).

In adopting the latter approach, the main issue is represented by the data exchange between the BIM platform and the VR engine. In fact, the BIM-to-VR workflow for importing BIM data into this type of software usually involves many steps, requiring also different levels of modeling and programming skills. Moreover, the import operations often rely on external plugins and add-ons that are typically from proprietary platforms. This also applies to HBIM-to-VR workflows, which often require various preparatory steps and tools just to visualize a heritage site in VR (Bolognesi and Fiorillo, 2023).

To tackle the above issues, some studies started to work on the automation of the workflow to facilitate BIM-to-VR integration by considering the Industry Foundation Classes (IFC) format (Natephra et al., 2017). This format is an open, international standard (ISO 16739-1:2024 (International Organization for Standardization, 2024)) following a specific schema that codifies a high number of elements of a BIM model besides geometric data, such as objects identity and semantics (e.g., name, type, etc.), their characteristics or attributes (e.g., material, color, etc.), and the relationships with other objects (Khorchi and Boton, 2024).

In the BIM-to-VR field, data stored in an IFC file are generally used for restoration and maintenance operations, or to support other construction works. However, when it comes to HBIM-to-VR, the possibility to seamlessly retrieve semantic data about specific objects can be particularly helpful also for other applications. For instance, these data could be used to enhance the cultural value of a certain CH site by focusing on storytelling for educational purposes (Oumoumen et al., 2024). These considerations emphasize how an enriched IFC model could be used not only to create a Virtual Environment (VE) that can be navigated by the users but also to build an interactive VHE, such as a virtual exhibition or a virtual visit.

However, to date, the adoption of IFC-based HBIM models for the creation of VHEs is mostly unexplored. According to current literature, the studies that proposed VR platforms specifically designed to automatically create VHEs like, e.g., the works by Hayashi et al. (2020) and Kiourt et al. (2016), retrieved geometric data (e.g., high-quality 3D models) and semantic data (e.g., cultural descriptions) from sources other than HBIM models.

On the one hand, this lack of adoption might be caused by the need of specialized skills both for the creation of the HBIM model and the VHE (Penjor et al., 2024), which complicates the process for non-IT users. On the other hand, some limitations still persist for HBIM-to-VR workflows utilizing IFC, such as the need to mitigate information losses while importing contents into game engines (Ferretti et al., 2022), as well as the lack of a standardization for storing CH data within an HBIM model (Suhari et al., 2024); furthermore, to the best of the authors' knowledge, there is currently not a standard approach to include into an IFC file the information needed for creating a VHE.

By building on the above observations, the research reported in the present paper aims to take advantage of the potential of HBIM models and the IFC standard to generate a VHE for a CH site. To achieve this goal, a novel semi-automated HBIM-to-VR workflow is proposed, composed of two main phases:

- A first phase, involving the manual enrichment of an IFC file associated with an HBIM model for the generation of a virtual visit. Essential features of this kind of VHE were identified by analyzing the current state of the art of workflows and platforms for the creation of VHEs. These features encompass the management of points of interest with descriptive data (text or multimedia CH contents), the capability to plan visitor's routes, the control of locomotion within the VE, etc.
- A second phase, utilizing a Unity-based VR platform that has been designed to automate several steps of the HBIM-to-VR workflow. This platform manages the data of the enriched IFC file, the related external files, the reconstruction of the VE and its object hierarchy, as well as the creation of the interactive experience. This approach enables the generation of a fully-featured virtual visit entirely at runtime, based on the enriched IFC file.

The devised workflow aims to contribute to the field of VHE creation by streamlining the process of transitioning from HBIM to VR, enhancing both accessibility and scalability. In order to demonstrate its potential, a use case is reported involving the creation of a virtual visit to the "Hall of Seasons" of Palazzo Carignano in Turin, Italy.

2. Related works

This section provides a review of the current state of the art in the field, covering key developments and methodologies in BIM, HBIM, and OpenBIM, HBIM-to-VR workflows, use cases of VR-based VHEs integrated with museum environments, and VHE authoring platforms from both the literature and the market.

2.1. BIM, HBIM, and openBIM

As mentioned in Section 1, the BIM methodology is proving very useful for digitizing and properly archiving the physical and functional data of buildings. As demonstrated in Babalola et al. (2021), in recent years, BIM has led to significant improvements in process management within the AEC industry and is widely adopted worldwide.

Although it was originally developed and is predominantly used in new construction projects, BIM started to be used also for historic buildings and, more in general, in the CH domain. In this case, the term HBIM is generally used. The modeling of historic buildings through HBIM must, however, adhere to distinct requirements compared to new constructions. HBIM is dedicated to creating 3D digital models that accurately represent not only the geometry of historic structures but also their material composition and historical attributes. These models are developed using data from photogrammetric surveys and laser scanning, integrating detailed and accurate information about existing structures (Lovell et al., 2023).

As illustrated in Achille et al. (2015), BIM modeling software varies in capabilities, with a primary focus on managing information rather than the complex geometry that is typical of historic buildings. The creation of an HBIM model, in turn, often requires the joint use of 3D modeling tools, like Blender or Rhinoceros, for managing point clouds derived from surveys and BIM-based software.

The enrichment of a BIM model for its use at different stages of a building's life cycle is governed by standards and norms like the EN ISO 7817-1:2024 (European Committee for Standardization, 2024) in European Union countries. These standards provide the geometric and information levels needed to create BIM models that can be used in the design, construction and operation phases. However, as discussed in Bianchini and Potestà (2021), the specific challenges encountered during HBIM modeling often cannot be addressed by these standards and thus require custom solutions. Given the need for continuous data exchange between different software to ensure collaboration among various experts and build complex applications, BIM (and HBIM) interoperability is a frequently discussed topic in the literature. A solution to avoid interoperability issues during modeling steps and the use of the model is the adoption of the openBIM methodology, which is defined as a collaborative process that is inclusive of all participants, promoting interoperability to benefit projects and assets throughout their life-cycle (Building Smart, 2010b). In practice, adoption of the openBIM methodology consists of using vendor-neutral formats like, e.g., the BIM Collaborative Format to discuss issues during modeling phases, CityGML to handle city-scale data, or IFC to share BIM model information as described in Building Smart (2010a). The development of the IFC file format is mainly due to buildingSMART.[1] This international community helps assets owners and the entire supply chain to work more efficiently and collaboratively through the entire project and assets lifecycle. The characteristics of this working methodology and the definition of IFC are also contained in the ISO 16739-1:2024 international standard.

The benefits of using openBIM for what it concerns data exchange are well-documented in the work by Oostwegel et al. (2022).

2.2. HBIM-to-VR

In recent years, the combination of HBIM and VR for the creation of VHEs has been explored by various works.

A common approach used by HBIM-to-VR workflows is to utilize game engines (e.g., Unity, Unreal Engine, etc.). For instance, Graham et al. (2019) explored the transition from BIM to VR by defining a system based on Levels of Detail (LODs) named LODIA. In their work, the authors presented a VR experience that guides the participants through a virtual narrative, emphasizing areas of higher fidelity to signify greater heritage value. The main challenge identified in the research was the complexity of converting detailed BIM models into optimized VR experiences while maintaining high visual fidelity, which requires extensive data management and technical proficiency. A similar conclusion was reached also in the work by Banfi (2021), which explored the evolution of interactivity, immersion, and interoperability in HBIM. In this case, the authors concluded that the technical complexity and the need for significant resources and expertise often pose limitations to the broader adoption of VR in the considered domain.

Another interesting work was carried out by Pybus et al. (2019), who presented an extensive workflow for converting HBIM to VR using game engines, focusing on the "Parliament Hill" site in Canada. Their approach involved several steps, including the collection of data, the manipulation of HBIM geometric data in external modeling tools (e.g., Rhinoceros), and the optimization of textures and materials for VR. Their workflow was aimed to create a high-fidelity VR experience while ensuring optimal performance for public dissemination. Despite the successful implementation, the process was resource-intensive and required significant manual intervention, highlighting the challenges of managing large datasets and ensuring interoperability between different software tools.

The latter aspect has been explored also by works that leveraged IFC-based approaches for importing HBIM models into game engines. As a matter of example, Ferretti et al. (2022) developed a semantically aware HBIM model based on "Palazzo Ducale" in Urbino, Italy, including an intelligent object parametrization. They also employed Unity to create a VR application for the digital curation and narration of CH contents. The HBIM model was enriched with detailed information about its inner elements, such as the artworks' catalogue numbers, author names and geolocation. However, the authors highlighted the technical complexity of importing an HBIM model as an IFC file into Unity without losing information, as well as the high computational costs associated with visualizing detailed HBIM models in VR.

Similarly to geometries, materials and textures in BIM models are not optimized for VR experiences. Few years ago, Duque Mahecha et al. (2021) explored the graphical dimension of IFC by proposing a UI to reassign textures for IFC-based VR applications. The UI was based on IfcOpenShell library,[2] an open-source IFC toolkit and geometry engine, and allowed users to assign an arbitrary image or file to each material previously defined in the IFC file. The output was a DAE file and a texture folder with all the involved textures. However, the texture mapping interface allowed the users just to scale or rotate the textures, which were repeated on the assigned surfaces without possibly considering an approach based on UV-coordinates. Moreover, most of the BIM-properties were lost when importing the IFC file into the VR environment, bringing the authors to consider an additional export of the IFC contents in the form of an XML file.

In conclusion, these HBIM-to-VR workflows offer a streamlined approach for importing HBIM models into development environments for VR applications. However, as discussed in the next section, VR-based VHEs require a range of functionalities beyond basic visualization, which cannot be managed either at the BIM level or through the standard IFC format.

2.3. VHEs integrated with museum environments

Museums have shown significant interest in incorporating VR experiences into their exhibitions, aiming to expand their role in the educational and cultural domains through the use of this technology (Spallone et al., 2024a). Nowadays, however, the most common scenario is that museums commission the development of custom VR applications to integrate virtual tours and exhibits into their offerings. Consequently, a challenge is to produce results that closely match the quality and functionality of applications created by professional developers. Various examples of such applications can be provided to identify the minimum level of functionality required.

A first example of the use of VR applications in the context of real-world museums is the work by Jung et al. (2016). The authors chose as a case study the Geevor Tin Mine Museum, in Eastern Cornwall, due to its focus on the integration of advanced technologies to enhance the visitor experience. In the experiment, visitors engaged with an immersive VR application (using a Samsung Gear device, hosting a smartphone), simulating the descent down the mining shaft and narrating the miners' initial entry into their work environment. Experiences of this type are characterized by a very limited interactivity, since the only interaction possible is to look around taking advantage of the 3 Degrees Of Freedom (DOFs) offered by mobile devices. Another limitation of this approach is related to the constrained computational resources available on such devices, which hinder high-quality graphical rendering in real-time or force the use of pre-rendered, non-interactive 360° photos and videos.

Another example is provided in Puig et al. (2020), where Puig et al. share insights from the development of two immersive VR experiences designed to complement a museum exhibition: a 360° video viewed through a Samsung Gear device, and a gamified, interactive VR experience using the HTC Vive kit (headset and hand controllers). The two experiences were part of an exhibition dedicated to the Neolithic settlement of La Draga at the Museu d'Arqueologia de Catalunya in Barcelona. To evaluate the user experience of VR as an enhancement to traditional museum visits, the authors recruited volunteers from museum visitors. In this case, they were given the opportunity to engage in the experience after attending a workshop led by an expert archaeologist specializing in the Neolithic period. The results revealed that user experience was closely tied to the visitor's prior experience with VR technology, highlighting the need to design experiences tailored to museum visitors who may face usability challenges. The use of more advanced VR systems, such as the HTC Vive, overcame the limitations of 3 DOFs and constrained computational resources, as it is

[1] buildingSMART: https://www.buildingsmart.org/.

[2] IfcOpenShell: https://ifcopenshell.org/.

a tethered system connected to an external workstation and supported by room-scale, 6 DOF tracking. In this way it is possible to create more complex and graphically richer VHEs, which can be navigated either through real walking within the constrained tracking area or by using artificial locomotion techniques with the hand controllers, such as teleportation (to specific teleport points or freely within designated areas) or smooth locomotion (also known as continuous movement). The hand controllers, also tracked by the system, allow users to interact with virtual objects and UIs, both through direct contact and at distance through ray casting.

A relevant use case worth to report is the VHE project “Mona Lisa: Beyond the Glass”, developed by the Louvre Museum (2019). This VR experience was designed to let users “step inside” the famous painting’s world, thereby providing a new form of accessibility and engagement. The VHE is distinguished by its advanced features, which include high-resolution digital renderings and interactive elements, fostering a multisensory engagement with the painting. Moreover, it includes an audio guide with a pre-recorded narration, providing visitors with an immersive experience of the famous painting. On the one hand, the usage of a pre-recorded voice allowed visitors to enjoy the virtual visit, fostering user experience and engagement. On the other hand, this approach requires to re-record the audio clip in case of an update to the narratives, unlike other workflows that utilize TTS technologies to generate the audio.

More recently, also Shahab et al. (2023) explored the potential benefits of using VR in museums, focusing on its impact on enjoyment and learning. In the study, carried out in the VRlab of the Deutsches Museum in Munich, Germany, visitors could engage with four VR experiences based on historically significant machines (the Apollo lunar roving vehicle, the Sulzer brothers’ steam engine, Otto von Lilienthal’s glider, and Carl Benz’s Patentmotorwagen). These machines were accurately reconstructed using laser scanning and satellite imagery to leverage the photorealistic rendering capabilities of VR technology. The VHE also supported interaction, including a lunar golf simulation. The results indicated that well-designed VR experiences, combining entertainment with education and fostering an adequate sense of presence, can significantly enhance both engagement and learning outcomes. However, the authors emphasize that museums must adapt their VR offerings to evolving technological advancements in order to meet visitors’ expectations.

Another recent example of VHE deployment in real museum settings is the work described by Restivo et al. (2023), which was showcased in the Kings’ Gallery at the Museo Egizio in Turin, Italy. This VR experience allows visitors to directly interact with museum objects within a VE. Set in a space reminiscent of a cultural center, users are seated across from a digital curator. Virtual remains are displayed on a table, and visitors can leverage hand controllers to closely examine and interact with them. In this case, the immersive VR experience is designed to avoid the need for artificial movements, and features a virtual agent (the curator) with TTS capabilities, enabling the contextual delivery of descriptive contents related to the remains. Both visitors and museum staff had positive responses, emphasizing the potential of VR as a supplementary tool to enhance traditional museum visits, rather than replacing them.

Based on the above review, it appears that VR applications developed for museums exhibit different features and levels of functionality, making it challenging to standardize the production process. Their creation and maintenance demand a wide range of specialized skills. In this context, a contribution towards simplifying and standardizing the creation of these experiences can be provided by platforms for authoring VHEs.

2.4. VHE authoring platforms

Outside the domains of BIM and HBIM, several studies have taken into account the need to simplify the creation of VHEs. These studies usually exploited VR platforms specifically designed to create a VHE. Such kinds of platforms generally aim to be user friendly and accessible, as well as to provide a series of tools letting users flexibly and easily manage the creation of the intended experiences.

The above goal has been showed over time to be reachable through different approaches. As a matter of example, some years ago Giangreco et al. proposed the VIRTUE system (Giangreco et al., 2019), a VR platform designed to create customizable and immersive museum experiences. The system was designed to allow museum curators to set up virtual exhibitions that include both static and dynamic 2D and 3D artifacts. It also allowed curators to design exhibition spaces with customizable textures, lighting, and sound; users could then navigate these VEs using VR devices. The lack of automation in placing the artifacts, however, was judged as a major limitation by the authors. More recently, Korkut and Surer (2024) proposed a framework to create PC, VR and Mixed Reality (MR) 3D environments based on “heterotopias”, defined as spaces that overlay multiple layers of reality to organize and experience knowledge. In their work, the authors specifically put the focus on virtual museums, employing a procedural algorithm for the management of the spatial and content layers of the environment. The framework included various capabilities in terms of content types support (text, images, audio, video, and 3D models), as well as an object parametrization to identify the main construction elements (e.g., walls, floors, roofs) useful for the creation of the digital environment. Zidianakis et al. proposed Invisible Museum (Zidianakis et al., 2021), a web application that aimed to democratize the creation of virtual exhibitions by providing an accessible tool named Exhibition Designer. The platform stood out for its flexibility, offering a range of ready-to-use templates, customizable floorplans, and comprehensive tools for adjusting spatial elements, exhibits, and lighting.

Other works explored alternative methods to develop VR platforms for creating VHEs, with many of them moving away from user-dependent functionalities and shifting towards nearly fully automated approaches. One of the first examples is reported in Amigoni and Schiaffonati (2009), where Amigoni and Schiaffonati presented Minerva, a system meant to revolutionize the creation of VHEs. The system was designed to assists museum curators by automating the preparation and allocation processes involved in organizing exhibitions. In the experimental phase, Minerva was used by museum curators to classify and allocate various artworks within a virtual representation of the Caserma Napoleonica in Milan, Italy. The results demonstrated the system’s potential to create effective VHEs, with positive feedback from the curators; nevertheless, they also highlighted the need to expand its application to a different spectrum of users. Goto et al. (2018) developed a similar system to automatically generate multiple museum scenes. The system was designed to take advantage of a database query language for the retrieval of 3D models and their associated data, while Unity was employed as VR platform for the generated VHEs. Hayashi et al. (2020) proposed a system for creating personalized virtual visits to museums based on user-selected artifacts. The system allowed users to curate their own virtual exhibitions by selecting images from sources like Wikimedia Commons. However, it only supported text and image contents. Some years ago, Kiourt et al. (2016) proposed a framework named Dynamus, designed to create VHEs. The framework followed a user-centric approach to let users easily create virtual museum experiences and included some interesting features such as the runtime content retrieval of 2D/3D data as well as the management of lighting and shadows.

Beyond the field of academic studies, the creation of VHEs has also been supported by several commercial authoring platforms. Also in this case, one of the main objectives of these platforms is to facilitate the planning, development, and sharing of VHEs, with particular attention to non-expert users (Kim et al., 2024). However, the quality of the VHEs that can be created with these platforms is highly dependent on the features and tools offered by each platform. In the following, a series of platforms are analyzed, highlighting their main objectives and features. These platforms were selected based on their relevance in terms of popularity within the CH domain, the number of features offered, and previous studies performed in the state of the art (Kim et al., 2024; Vital et al., 2023; Sylaiou et al., 2024).

Kunstmatrix (Kunstmatrix, 2024), for instance, is an online platform designed for creating and curating professional 3D virtual art galleries and exhibitions. It enables artists, curators, and galleries to display artworks, sculptures, and multimedia pieces in customizable virtual spaces. The platform also supports immersive VR with headsets such as Meta Quest or HTC Vive, and allows for the creation of guided visits by defining specific guiding points. This approach facilitates the creation of a VHE, although users are limited to the platform's predefined exhibition spaces. Moreover, it seems that the possibility to upload the artworks is restricted to images only, without considering 3D models or other multimedia contents.

Another platform for creating virtual exhibitions is *ArtPlacer* (ArtPlacer, 2024), which is specifically designed for artists who want to exhibit and sell their works. In this case, in addition to predefined spaces, custom VEs are also available, along with a limited set of features to customize the environment, such as textures and colors for walls, floors, and ceilings. Currently, however, the platform does not seem to support the viewing of created virtual exhibitions with VR headsets.

A wider set of features for creating a virtual exhibition is offered by the desktop VR web platform *New Art City* (Hanson, 2024). The platform allows users to create immersive experiences in customizable VEs, with the ability to upload 3D models, audio, images, and videos. Additionally, users can modify various settings of the virtual world (e.g., sky color, floor type) and add interactive objects within the exhibition. A specific feature also allows users to define the reflection type for reflective materials, although it does not offer full control over the lighting of a VE. Furthermore, unlike the previous platform, it does not provide any predefined spaces, requiring users to import 3D models from other sources.

One of the most relevant means for creating VHEs is the web platform *Artsteps* (Dataverse Ltd, 2024), which is specifically designed for building, exploring, and sharing interactive 3D virtual exhibitions. Starting with an empty space, users can create and customize the exhibition area using the tools provided by the platform, as well as by uploading 3D models, images, audio, and text. Users can also choose to purchase predefined VEs directly from the platform, eliminating the need to create them from scratch. Another feature offered by the platform concerns the possibility to define a narrative using guiding points, which can be placed at specific spatial locations within the VE. Immersive exploration with VR headsets is supported, along with a limited set of interactions with objects within the environment. However, the management of lighting and reflections is not currently available on the platform, which may limit the ability to create realistic environments.

A promising alternative to the previous platforms is *VR-All-Art* (Jevremovic and Fuerer, 2024), which aims to support the creation of virtual exhibitions for galleries, artists, and museums. The platform supports both public and private exhibitions, providing tools for creating VHEs that can be accessed globally through VR headsets or mobile devices. In this case, the VE can be built upon a real-world space and customized with external 3D models. Additionally, the platform allows for the definition and management of lighting within the VE, although it lacks features for handling reflections. Currently, the platform is not free to download and appears to be targeted towards expert and professional users.

The common goal of the approaches and platforms analyzed so far is to obtain VR-based VHEs. However, as shown in Table 1 where key characteristics are summarized, each approach and each platform has its own set of features and limitations. Furthermore, none of them can produce a VR application offering all the functionalities available in common VR applications specifically developed for museums, nor can match the same level of quality.

2.5. Considerations

Based on this review of the state of the art, it appears that the integration of BIM, HBIM, and VR has shown significant potential for creating effective VHEs. However, current processes are often manual, involve the use of multiple tools, and require advanced technical expertise, which limit the widespread adoption of these technologies. At the same time, the spread of platforms aimed to facilitate and automate these approaches making them available to a less experienced audience is still characterized by various limitations, and the results are qualitatively inferior to the custom solutions currently adopted in the museum industry.

Creating realistic VEs is one of the primary challenges. Although most platforms offer various customizable features, such as textures and lighting adjustments, these options are not always sufficient to create a truly realistic environment. Moreover, the lack of advanced features, such as dynamic lighting, reflections, and LOD management, may limit platform's ability to deliver immersive and optimized VHEs. This is especially true for authoring platforms, which often prioritize simplicity in the user workflow by offering a limited set of features. All these factors can become critical constraints when it comes to user engagement, particularly for virtual museums or narrative-based experiences.

Another aspect to consider is the reliance on predefined VEs or external data. Several authoring platforms, for example, offer predefined templates or allow users to import 3D models from external sources to populate an empty virtual space. On the one hand, this approach simplifies the creation of a VHE for non-expert users. On the other hand, different platforms often rely on proprietary formats and workflows, which could lead to interoperability issues for professionals. Additionally, data related to the VHE are often confined within the platform (e.g., predefined VEs) or uploaded directly by users (e.g., 3D models, images, videos), which may not be ideal from a standardization perspective.

Regarding the field of HBIM, previous works have also highlighted some challenges. Many studies involving the creation of a VHE encountered the need to import HBIM models into a game engine. Given that both geometrical and semantic data are involved in the workflows, many approaches shifted towards an automated method for importing these data. This choice allows for easier importation of HBIM models and provides the ability to modify both geometrical and semantic data without having to manually re-import them for each change. Nevertheless, the topic of automation in deploying the VHE itself appears to be under-addressed, even though it could be a key element to further enhance workflows in terms of scalability, time, and resource efficiency.

Finally, some of the analyzed platforms rely on interaction and guidance systems to both engage users and provide guidance within the experience. However, these interactions and guidance systems are often quite simple and lack certain functionalities, such as audio generation capabilities (e.g., TTS) or dynamic UIs (e.g., adaptive UI panels). Moreover, users often have to manually input cultural information (e.g., artwork descriptions) directly into the chosen platform in order to visualize it through the UI, which can impact interoperability and standardization.

These considerations highlight the need for interoperable and standardized formats that include not only metadata for creating realistic and interactive VEs (e.g., geometries, material parameters), but also semantic data (e.g., artwork descriptions) and settings (e.g., guiding point positions) to create engaging and immersive VHEs.

Based on these considerations, the workflow proposed in the present paper stands out by significantly simplifying the creation of VHEs from HBIM-related IFC files. By using IFC as a comprehensive data storage, the devised workflow facilitates the construction of data relationships, enabling the reconstruction of VEs with high fidelity and interaction capabilities by leveraging the rich information embedded in HBIM

Table 1
Main features of existing VHE authoring platforms analyzed in Section 2.4, compared with the solution proposed in this paper.

		Kiourt et al. (2016)	Korkut and Surer (2024)	Amigoni and Schiaffonati (2009)	Giangreco et al. (2019)	Hayashi et al. (2020)	Zidianakis et al. (2021)	Goto et al. (2018)	Dataverse Ltd (2024)	ArtPlacer (2024)	Kunstmatrix (2024)	Jevremovic and Fuerer (2024)	Hanson (2024)	This work
VR technology	Immersive VR	✓	✓	–	✓	–	✓	✓	✓	–	✓	✓	–	✓
	Desktop VR	✓	✓	✓	–	✓	✓	–	✓	✓	✓	✓	✓	✓*
External data retrieval	Text descriptions	✓	✓	✓	–	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Images	✓	✓	–	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Videos	–	✓	–	✓	–	✓	–	✓	–	–	✓	✓	✓
	Audio descriptions	–	P	–	P	–	P	–	P	–	P	P	P	G
	3D models	✓	✓	✓	✓	–	✓	✓	✓	–	✓	✓	✓	✓
	BIM information	–	–	–	–	–	–	–	–	–	–	–	–	✓
Graphics and rendering	Lighting management	G	G	–	G	P	G	–	–	P	–	G	G	G/P
	Reflections management	–	–	–	–	P	–	–	–	–	–	P	–	G
	LODs handling	–	–	–	–	–	–	–	–	–	–	–	–	✓
Locomotion system	Teleport points	–	–	✓	✓	✓	✓	–	✓	✓	✓	–	–	✓
	Teleport areas	–	✓	–	✓	–	–	–	✓	–	✓	✓	✓	✓
	Continuous movement	✓	✓	✓	–	✓	✓	–	✓	✓	✓	✓	✓	✓
User Interface (UI)	UI panels	✓	✓	–	–	✓	✓	–	✓	✓	✓	–	✓	✓
	UI buttons	–	✓	–	–	✓	✓	–	–	–	✓	✓	✓	✓

✓ = Available, – = Not available, ✓* = Planned as future work, G = Generated, P = Predefined.

models. Additionally, the proposed workflow leverages a VR platform that can be used to semi-automatically generate the VHE starting from the enriched IFC file, thus streamlining the development process and opening it up to non-experts.

3. Materials and methods

According to the analysis reported above, current methods for creating VHEs from HBIM data face challenges such as limited interoperability, manual workflows, and lack of standardization. The proposed workflow addresses these issues by streamlining the creation of immersive, interactive VHEs through two main phases, i.e., preparation and deployment. The preparation phase involves exporting data, enriching the HBIM model within the IFC file, and storing associated external data. In the deployment phase, the VR platform is used to dynamically generate a virtual tour from the enriched IFC file and its related external data, providing an immersive VHE at runtime.

The VR platform, developed using the Unity game engine, supports a wide set of functionalities for the creation of VHEs. Specifically, it follows a runtime approach for the retrieval of the data, the loading of the external files, the reconstruction of the HBIM model in terms of geometric and semantic data in the IFC file, and the generation of the VHE. The HBIM reconstruction, in particular, is handled through the use of IfcConvert, a tool provided by IfcOpenShell. The platform has been designed to support also a number of other features, such as space adaptive lighting and reflections, LODs handling for high-poly meshes, and real-time audio generation via TTS ElevenLabs API.[3]

3.1. Preparation phase

This subsection illustrates the preparation and exporting of the data, including the enrichment of the HBIM model in the IFC file and the storage of its associated external data. Specifically, the external data considered include the textures and UV coordinates of the environment, as well as additional 3D meshes semantically linked to the HBIM model required for the VR visualization.

Several software tools are employed in the process. In particular, Autodesk Revit suite is used to develop the HBIM model and export the IFC file. The texturing and the exporting of models data are managed using the Blender 3D modeling software and a Python script.

3.1.1. From the HBIM model to the enriched IFC file

The devised workflow starts from the definition of the contents that it is necessary to include within the HBIM model. The definition of the IFC entities, i.e., the different objects to which geometries and parameters can be associated, is a key step in creating the enriched IFC file, capable of storing the information needed to create the VHE.

The VHE is structured as a virtual visit and is based on a series of Points of Interest (POIs). The POIs are essentially a conceptualization of a specific observation point inside the environment, which corresponds to a location where the user can learn something about the specific heritage site (Spallone et al., 2024b). The other elements that it is crucial to identify within the HBIM model are the Look-at Objects (LAOs), such as decorations, artworks and architectural elements. Each LAO will be associated with one POI through the BIM Property Sets (Psets) definitions. The specification of these contents passes through the enrichment of the model with a series of parameters, listed in Table 2.

In particular, POIs are equipped with a custom Pset named *Pset_POI*, which contains three parameters:

- *ID*: an integer value that is used for identify uniquely the POI during the visit;
- *Sequential*: a boolean value, indicating whether the POI will follow a sequential approach to show the associated LAOs to the user (alternatively, a free exploration will be allowed);
- *Description*: a textual description of the POI, which is optional but can be used to provide useful information about the specific spatial position of the POI (e.g., the introductory sentence of the first POI could vocally welcome the user into the experience).

The LAOs are equipped with another Pset, named *Pset_LookAt*, which contains five parameters:

- *ID*: the name used to uniquely identify the LAO within the VE;
- *View_Point*: the identifier of the POI simulating the observer's position; this parameter permits the identification of the POI that should contain the LAO, which implies that a POI could have multiple LAOs;
- *ImageURI*: a text value containing the path of an image linked to the LAO, which will be presented to the VR user after the activation of the LAO;
- *VideoURI*: a text value optionally containing the path of a video linked to the LAO, which could be visualized when the LAO is active by clicking on a specific button;
- *Order_Index*: an integer value indicating the order of the LAO if it is part of a sequential POI;
- *Description*: a text value describing the LAO, which will be presented to the VR user both vocally and visually.

As a final step, the HBIM model is also endowed with a Pset named *Pset_Material_Rendering_Properties* for each *IfcMaterial*. This Pset contains a set of properties useful to reconstruct the material appearance once the environment will be rebuilt into the VR platform. More specifically, six parameters are defined:

- *IsTriplanar*: a boolean value, indicating whether the material uses triplanar mapping (true) or UV mapping (false);
- *Roughness*: a float value, representing the roughness of the material's surface, where 0.0 is completely smooth and 1.0 is completely rough;
- *Metallic*: a float value, indicating the metallic nature of the material, where 0.0 is non-metallic and 1.0 is fully metallic;
- *Transparency*: a float value, indicating the transparency level of the material, where 0.0 is completely opaque and 1.0 is fully transparent;
- *Tiling_X*: a float value, representing the horizontal tiling factor of the material's texture (it indicates how many times the texture repeats per meter along the X axis);
- *Tiling_Y*: a float value, representing the vertical tiling factor of the material's texture (it indicates how many times the texture repeats per meter along the Y axis).

3.1.2. Texturing and UV mapping

In order to enrich the geometric data provided by the HBIM model, the workflow includes a texturing and UV mapping step using Blender. This approach is essential in real-time graphics applications where high levels of visual detail cannot be achieved by relying solely on the 3D model's basic geometry and material information from the BIM data (such as vertices and material properties). In this step, an image texture (e.g., a PNG file) is assigned, and UV coordinates are defined for each 3D model. The texture provides the visual appearance of the model, while the UV mapping specifies how the texture is applied, making it the primary method for representing detailed elements typical in VHEs, such as paintings, photographs, and transcriptions. In this step, version 4.1 of Blender is used, along with the IfcOpenShell Blender-BIM add-on. This tool offers several functionalities for importing, editing, and exporting of BIM models as IFC files. With Blender it is also possible to perform manual UV mapping on individual meshes of the model and assign one or more materials to different parts of the geometry. This

[3] ElevenLabs API: https://elevenlabs.io/api.

Table 2
IFC entities and parameters defined within the HBIM model.

Object	Class	Type	Pset	Parameter name	Parameter type
Point of Interest	*IfcBuilding Element Proxy*	POI	Pset_POI	ID Sequential Description	Int Bool Text
Look-at Object	General	General	Pset_LookAt	ID View_Point ImageURI Order_Index Description	Text Int Int Int Text
Material	*IfcMaterial*	NA	Pset _Material Rendering Properties	IsTriplanar Roughness Metallic Transparency Tiling_X Tiling_Y	Bool Float Float Float Float Float

step is essential since some functionalities of the IFC format, including those regarding textures and UVs, are not always fully supported by BIM platforms. These functionalities are nonetheless very important to provide the model with a visual quality appropriate for a virtual visit.

The main technique for supporting textures in the IFC format is through the *IfcSurfaceStyle* entity, which incorporates different subentities, such as *IfcSurfaceStyleWithTextures*, containing a reference to an additional entity named *IfcImageTexture*. The latter usually points to an external image file (JPG, PNG, etc.) via URI or is directly included in the file as an array of pixels. Similar entities are used for the UV coordinates, such as *IfcTextureCoordinates* and *IfcTextureMap* (BuildingSmart, 2020a). However, as said, not every BIM platform tend to prioritize the support for entities regarding textures. This fact makes the exporting of IFC files with textures quite complicated. Moreover, workflows including game engines often require proprietary add-ons and tools, sometimes very expensive, to import the textured IFC file. For these reasons, in the proposed workflow, an alternative approach was adopted to allow a custom exporting and importing of the textures and the UV coordinates data from Blender to Unity.

After the texturing and UV mapping of the geometry, texture data is exported in a local folder named “TextureData” by running a custom Python script directly in Blender. More specifically, UV mapping data are exported in a JSON file containing, for each mesh, the coordinates of the vertices and the associated UV coordinates identified using their *GlobalId*. The latter is a univocal alphanumeric identifier gathered directly from the HBIM model. The Python script also exports in the same local folder all the textures as PNG files for each material of the HBIM model.

3.1.3. High-definition models

In order to keep the enriched IFC file lightweight, to proposed workflow supports the integration of high-poly 3D models, referred to as High-Definition Models (HDMs), without incorporating them directly into the HBIM model as geometrical data, but instead as textual identifiers. These identifiers can later be used to retrieve the corresponding models, stored externally, when necessary (e.g., in the VHE experience).

Each HDM is associated with a specific LAO within the HBIM model via a unique identifier (*ID*) available in the LAO’s Pset. In the HBIM model, these LAOs are represented by placeholder meshes, referred to as Dummy Meshes (DMs).

All the HDMs are stored in a custom local directory named “HDModels”, where each HDM is located in its own subfolder corresponding to its associated HBIM object. Since the devised VR platform supports different LODs for each mesh, a general subfolder may contain multiple mesh files.

In the use case considered in the present paper, all the HDMs were created using the GLB format, an open-source, versatile, and widely-used 3D file format. This choice allows the VR platform to retrieve easily the HDM associated to each DM in the HBIM model and place them in the VR environment.

3.2. Deployment phase

The deployment phase utilizes the designed VR platform to generate an engaging and visually appealing VHE from the enriched IFC file and the related external data. As it can be seen from the review in Section 2.4, several functionalities required by such a platform (e.g., parametrization, data retrieval, etc.) seem very suitable for BIM-based approaches, since the semantic data about configuration parameters and cultural contents are directly available in the HBIM model.

The VHE built by the platform is structured as a guided visit. During the visit, both visual and auditory guidance is provided to the visitor in order to move from one specific spatial point of the VE to the other. For each of these spatial points, the visitor is supported by the platform in learning specific contents about visual, interactable elements present in the environment (e.g., artworks within a museum). Details are provided in the next subsections.

3.2.1. VR deployment platform

For the development of the deployment platform, Unity version 2021.3 was chosen. However, in principle, any game engine capable of supporting the automatic processing of contents encoded within the enriched IFC file could be used.

For immersive VR support, the SteamVR library was utilized to provide the basic functionalities required to interact with the VE. Alternatives such as OpenXR, which offer similar levels of functionality, could also have been used. Specific support for non-immersive VR is currently under development.

To minimize potential cybersickness issues (Calandra and Lamberti, 2024), teleportation was selected as the primary locomotion method, given its frequent use in immersive VR experiences within the CH domain (Spallone et al., 2024a). Additionally, continuous movement, also known as smooth locomotion or joystick movement, has been incorporated, reflecting its status as the standard for commercial VR applications (Cannavó et al., 2021).

In the current implementation, data are retrieved from local folders. However, the platform has been designed to replace local folders with a cloud-based retrieval system. It is also worth remarking that the platform was deployed as a PC application rather than a standalone one, to ensure better performance in terms of graphics quality and frame rate.

The operation of the platform involves several steps: the gathering of the IFC data, the HBIM model reconstruction, the handling of the graphics features (materials, textures, and lighting) and rendering, and the initialization and management of the generated VHE.

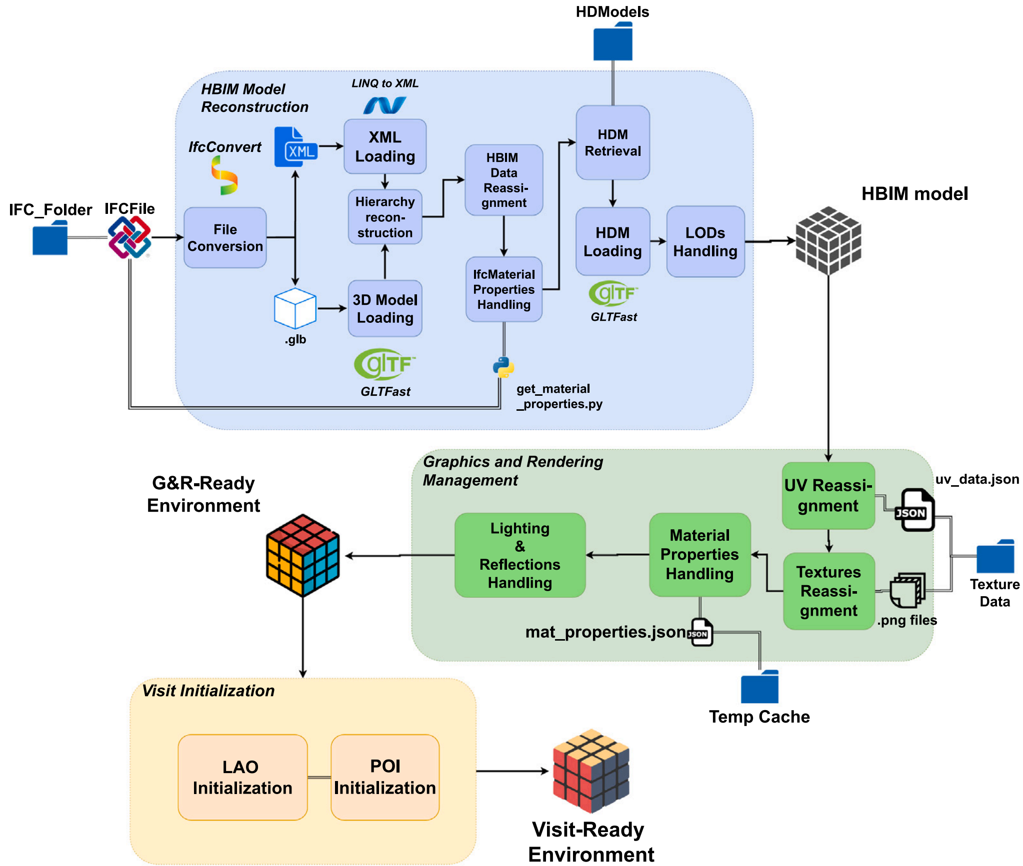


Fig. 1. Schematic representation of the three steps performed by the VR platform once the user has chosen the environment to build.

3.2.2. Data gathering

Once the user has decided which environment to build, required data are directly gathered from a local folder named “IFCFiles”, containing one subfolder for each HBIM model available. Each subfolder in turn contains the IFC file, the “TextureData” folder and the “HDModels” folder, both exported during the data preparation phase.

The user can then start the VHE generation process, which consists of several steps carried out automatically by the platform. These steps encompass the HBIM Model Reconstruction, the Graphics and Rendering Management, and the Visit Initialization. A schematic representation of the three steps is provided in Fig. 1.

3.2.3. HBIM model reconstruction

The main purpose of this step is to retrieve HBIM data from the IFC file selected previously, as well as the HDMs semantically linked to it. Thus, the VR platform loads them into the VE, also managing LODs for the HDMs.

Firstly, the platform automatically extracts both geometric and semantic data from the retrieved IFC file. This is done by leveraging the functionalities offered by IfcConvert v.0.7.0, which supports the conversion of a generic IFC file in several formats (IfcOpenShell, 2022). As said, in the case of this work, geometric data are converted in a GLB file, while semantic data are extracted and written in an XML file. When the conversion ends, both the files are saved in a temporary local folder acting as a cache.

Afterwards, the platform proceeds with loading the above files in the Unity environment. More specifically, the GLB model is uploaded in the active scene of the VR platform by using the GLTFast v.6.7 module available directly in Unity (Unity Technologies, 2023). The loading of the XML file is made possible by utilizing LINQ to XML, a component of the Microsoft .net framework that enables the manipulation of XML files (Wagner et al., 2021). As soon as the loading is completed, it is possible to perform the hierarchy reconstruction and the HBIM data reassignment.

As soon as BIM data is fully set up and the hierarchy is reconstructed, the HDMs related to the HBIM model are retrieved. Currently, the platform retrieves the HDMs for specific objects important for the virtual visit (e.g., decorations, statues etc.), emphasizing their heritage value through a visual quality as high as possible. If present, the platform loads multiple versions of each HDM with different levels of detail to manage the LOD in the virtual scene.

Once the retrieval of the HDMs ends, the HBIM Model Reconstruction step can be considered as completed. The output for this step is the reconstructed 3D model of the environment.

3.2.4. Graphics and rendering management

After the HBIM model is reconstructed, the VR platform begins the Graphics and Rendering Management step. The purpose of this step is to realistically represent the VE by assigning UV coordinates and textures, setting material properties, and managing lighting and reflections.

The first task is UV assignment for the HBIM model’s meshes. UV data are extracted from a local JSON file created during data preparation using a custom component. This component iterates through the model’s meshes to match GlobalIds with those in the JSON file, reassigning UV data when a match is found.

Next, the platform reassigns textures. From the local folder containing the JSON file, a custom component retrieves textures for each mesh based on file labels. Specifically, it searches for matching GlobalIds in a folder named “TextureData”. If a match is found, the texture is loaded and assigned to the correct material. Each texture is also labeled by type, allowing accurate association with the material’s properties. As a matter of example, a texture named “3dx9421_01_NORMAL” would be assigned to the first material of the object whose GlobalId is “3dx9421” in the parameter corresponding to the NormalMap.

Once the textures are applied, the material properties extracted from the IFC file during the HBIM Model Reconstruction step are assigned to each material. Specifically, the platform assigns values to parameters such as *Triplanar*, *Roughness*, *Metallic*, *Transparency*, *Tiles_X*, and *Tiles_Y* from the *Pset_Material_Rendering_Properties* property set defined in the HBIM model.

The last operation is the management of lighting and reflections. The lighting management involves both predefined lights and generated lights. The VE is equipped with a directional light acting as a sun-like light source. This type of light is predefined and follows a real-time approach to adapt to different environments. Additionally, the VR platform creates a spotlight in front of each LAO found within the HBIM model. These are also real-time lights and allow to attract the attention of the VR user on all the LAOs in the environment, highlighting their details. For what it concerns reflections, since from the HBIM model it is possible to extract the elements representing the walls of the environment, the VR platform identifies in the hierarchy all the objects whose type is *IfcWall*. Then, it calculates the Bounding Box (BB) surrounding all the *IfcWall* elements to set the area of influence for the reflections. More specifically, a Reflection Probe (RP) Unity component is added into the environment in order to obtain reflections for the materials that need them (e.g., mirrors, metallic surfaces, etc.). Then, the RP's location and dimensions are matched to the center and size of the calculated BB.

The output for this step is a graphics- and rendering-ready environment.

3.2.5. Visit initialization

Once the Graphics and Rendering Management step is completed, the VR platform performs the initialization of the VHE. This step allows the creation of the actual virtual visit, as well as of the components required to support user's locomotion and interaction within the VE.

The two fundamental entities involved in this step are the POIs and the LAOs. Firstly, the platform gathers every POI present in the IFC model. Each POI is then equipped with a Teleport Point (TP) component from the SteamVR kit, which allows the user to teleport to the POI position into the VE. When using this locomotion technique, upon teleporting to a specific TP the contents related to the corresponding POI are activated (e.g., starting the playback of audio tracks, or displaying UI panels with text and images). When continuous movement locomotion is used, the trigger occurs through direct contact between the user and the TP's collider. This kind of management allows to put the focus on specific locations of the VE, possibly enhancing the user's perception and attention. However, it may restrict the area of movement of the user. To deal with this possible issue, the VR platform also supports the creation of SteamVR Teleport Areas (TAs), which allow users to move more within the VE by teleporting to any point within designated areas. The TAs are automatically defined by identifying the *IfcFloor* entities in the HBIM model. A similar procedure is performed to gather all the LAOs and their properties. During this operation, the platform assigns all the LAOs to their POIs. The information about the relative POI is contained in the *View_Point* parameter within the *Pset_LookAt* Pset of the considered LAO.

The output for this step is a visit-ready environment.

3.2.6. Visit management

When all the previous steps are completed, a preview of the reconstructed environment is presented to the VR user as an introduction to the VHE. More specifically, the environment is displayed as a scaled-down, 3D miniature of the actual space with a grey material. This step is useful for verifying the correct loading of the HBIM model and the associated external data. It is also possible to switch from a solid model view to a wireframe view, allowing the visual inspection of internal elements, such as POIs, without any occluding object (e.g., walls).

If the generation process is successful, the user can start the virtual tour. The full-scale environment is enabled, and the user is positioned

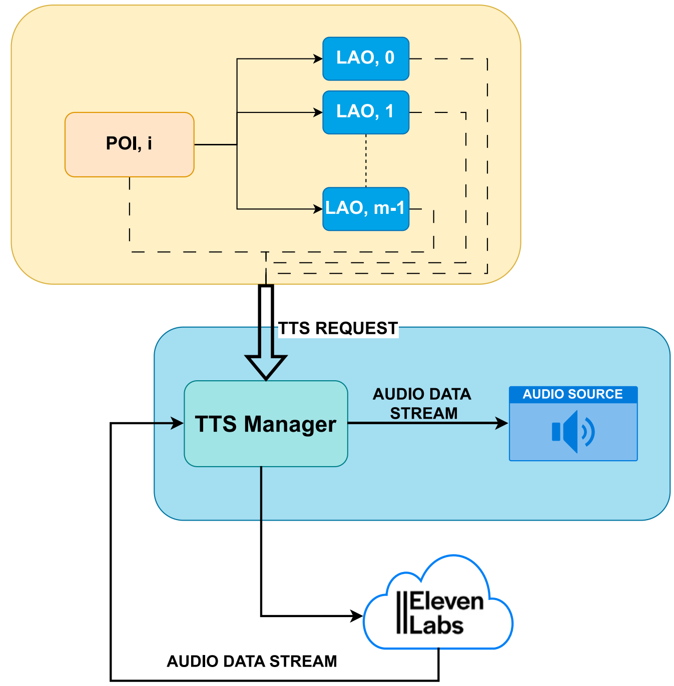


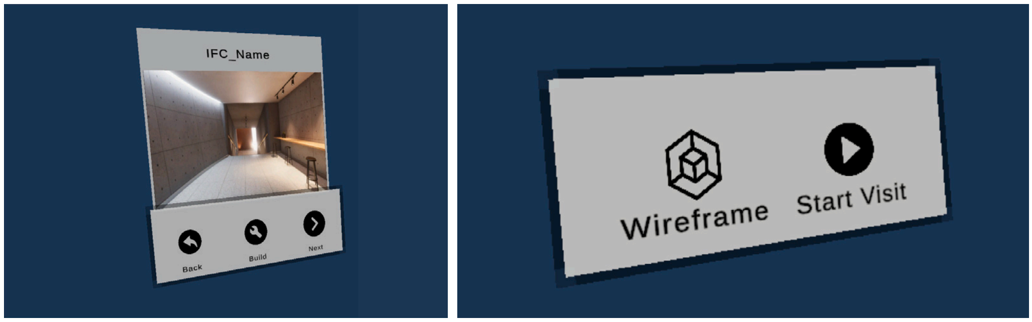
Fig. 2. Schematic representation of POIs and LAOs handling. In this case, the *i*th POI handles all the LAOs contained in it. As shown, both POIs and the LAOs have the capability of sending TTS requests to the TTS Manager.

in the first POI. The management of the visit is assigned to a custom component named Visit Manager (VM), which is responsible for guiding the user throughout the whole experience. More specifically, the VM handles the activation of the POIs along with their TPs, as well as the activation of the TAs present in the environment.

The VR user is vocally guided in the experience by a synthetic voice created using the ElevenLabs API, which handles the TTS conversion. The text converted in speech during the process is either predefined or gathered from the semantic data within the reconstructed HBIM model. The management of the TTS requests is handled by another custom component, named TTS Manager, which handles the communication with the ElevenLabs API.

When the visit is started, the VM unlocks the first POI. When a POI is unlocked, the following procedure is executed (see Fig. 2):

- A TTS request is sent to the ElevenLabs API with the text contained in the *Description* parameter of the POI; this text provides a vocal description of the current location of the user;
- After a brief interval, another TTS request is made to vocally announce the number of LAOs for the POI.
- Based on the actual value of the *Sequential* parameter of the POI, the following two pathways are possible:
  - Sequential POI
    - The list of LAOs within the POI is sorted out based on the *OrderIndex* parameter of each LAO;
    - A UI panel is instantiated for each LAO in the sorted order, displaying information such as description, title, and images;
    - Simultaneously, a TTS request is sent with the *Description* parameter of the LAO, providing a vocal explanation to the user;
    - Once the explanation ends, a UI button appears next to the panel, allowing the user to proceed to the next LAO in the sequence;



(a) (b)

Fig. 3. Example of UI elements included in the application (main menu UI as reference): allowing the user to (a) select the environment to reconstruct and visualize relevant information, and (b) choose whether to make the 3D miniature of the environment transparent to display points of interest (POIs) or begin the virtual visit.

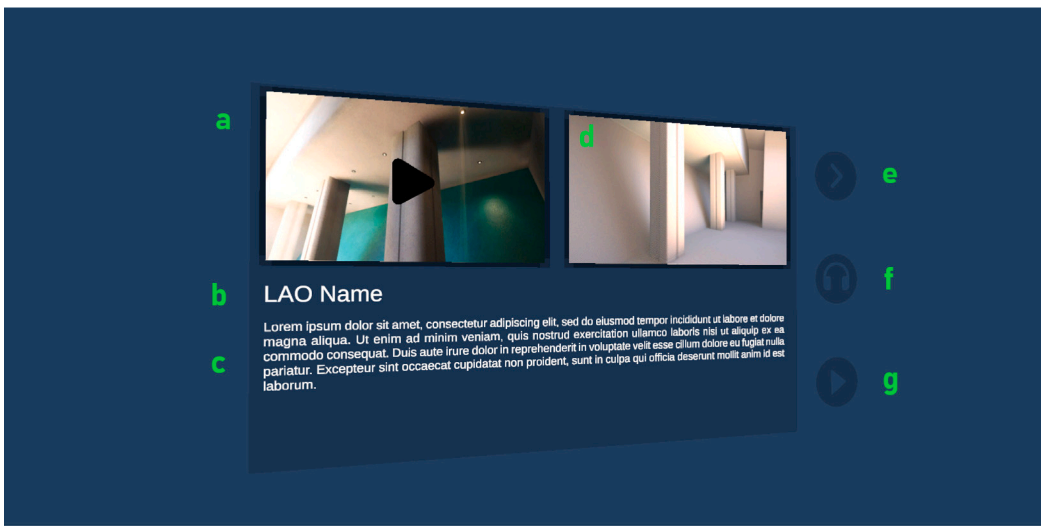


Fig. 4. An example of UI panel, used to present a LAO to the user within the VHE.

  - This process is repeated until all the LAOs have been considered.
- Non-sequential POI
  - The list of LAOs is not sorted out;
  - A UI panel is instantiated for the first LAO in the list, and the user can navigate between LAOs using a UI button; in this case, TTS requests are not sent automatically, but triggered by the user, thus providing flexibility as POIs can be explored at own pace.

- The next POI is unlocked, and a TTS request is made to vocally inform the user that the next POI is available.

This procedure is then iterated for each POI the VR user encounters during the visit.

3.2.7. UI elements

As mentioned in the discussion reported in the previous subsections, interaction with the VR environment passes through a series of UI elements, such as UI buttons and UI panels (Fig. 3(a)). The user can interact with these elements using a laser pointing mechanics. This mechanics is very common in VR applications as it allows the user to handle a number of different interactions.

The cultural contents regarding the visit are presented through UI panels instantiated at runtime whenever a LAO is presented to the VR user (Fig. 4).

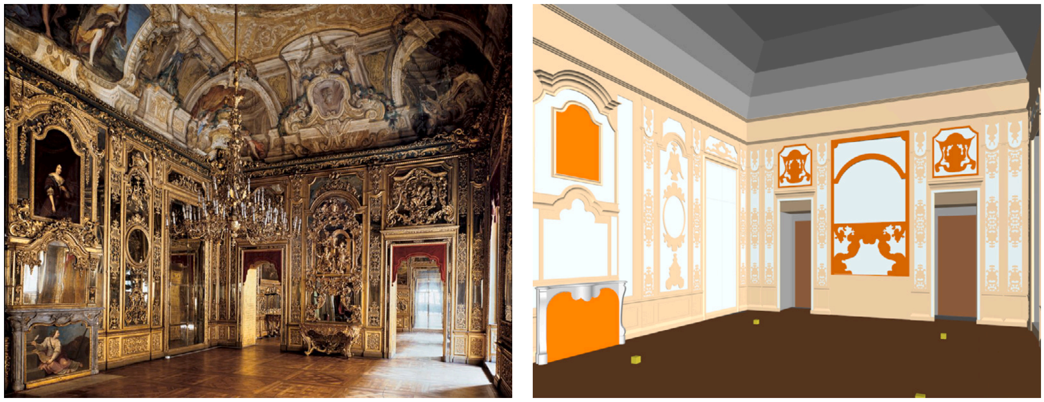
The UI panel contains the following elements:

- A UI panel (indicated with a in the figure) equipped with a render texture component that shows a video indicating the position of the LAO within the environment; the render texture shows the point of view of a camera positioned at the center of the VE, which initially frames the current POI, then shift to the LAO after a brief interval; this allow the user to easily identify the LAO in the environment;
- Two textual UIs (b and c) displaying the name and description of the LAO, respectively;
- Another UI panel (d) that loads an image using the URI stored in the *ImageURI* parameter of the LAO;
- Three UI buttons (e, f and g): one disabling the current LAO's UI and switching to the next LAO, another one sending, when clicked, a request to the TTS API to vocally read the LAO description to the VR user, and a last one showing a panel UI that loads a video using the URI stored in the *VideoURI* parameter of the LAO.

This setup supports an informative, guided visit as the user explores the VE and interact with the provided contents.

4. Use case

In order to showcase the capabilities of the workflow presented in this paper, it was decided to apply it to a use case regarding the creation of a virtual visit to a significant and iconic Italian CH site: Palazzo Carignano in Turin. Palazzo Carignano is a historic building built in 1680 by the architect Guarino Guarini. Initially constructed



(a) Actual hall (b) BIM model

Fig. 5. Picture of the selected hall for the proposed use case, named "Hall of Seasons", reconstructed with surveys and analysis of historical data.

as a residence, it became the seat of the first Italian parliament in 1861. The authors are conducting various experiments on potential CH applications of HBIM models of the palace. In Rimella et al. (2023), the working method that led to the definition of the HBIM model of Palazzo Carignano is described, illustrating how different representation scales entail different usage scenarios.

The HBIM model of the palace consists of several federated models, coordinated to refer correctly within the general model. However, not all the models that define the HBIM were used. The use case focused on the "Hall of Seasons", part of the Princely Apartments and an example of Piemontese Baroque style (Cerri, 1990) (Fig. 5). Fig. 5(a) shows a picture of the room that was the subject of the case study, with the details and decorations typical of the Piedmontese baroque, whereas Fig. 5(b) shows the HBIM model recreated using surveys and historical data; in this figure, POIs and LAOs are also highlighted (in yellow and orange, respectively).

The devised workflow involved the use of an IFC BIM file to create a virtual visit of the room, thus identifying the decorative objects typically included in the real visit. Thus, the HBIM model was enriched using Revit with the necessary parameters to identify the LAOs in the VE. Additionally, six POIs were placed within the hall to identify the observer's position in the exported IFC model.

The exporting of the HBIM model in IFC format was carried out by creating an MVD (Model View Definition) (BuildingSmart, 2020b), which identified the portion of the model to be exported and the Psets containing the parameters defined in Revit to be associated with the IFC model. The exporting method followed the definition of IFC4 version. Specifically, the elements placed in the hall to simulate the observer's position were exported as *IfcBuildingElementProxy* of type POI. These elements were associated with a *Pset_POI* containing the ID and the other parameters defined in Section 3.1. The LAOs identified for the virtual visit included the frescoed vault, defined as *IfcCovering* of type Vault, and some of the room's wall decorations, defined as *IfcBuildingParts* of type Decoration.

In addition to creating the enriched HBIM model, an on-site survey in the hall was conducted. The survey was aimed to capture high-quality textures for various elements of the environment (floor, ceiling, etc.) and perform 3D scanning of decorations depicting the four seasons which give the hall its name to develop the HDMs. The survey was performed using a portable F6 laser scanner, which produced dense point clouds for each decoration. These point clouds were meticulously cleaned and processed to create meshes that represent the decorations with millimetric precision. The processing and export of the point clouds were carried out using MeshLab version 2022.02, an open-source software commonly used for editing and processing 3D meshes and point clouds. Each point cloud was processed three times to create three LODs. The LODs were generated by reducing the number of vertices in each subsequent mesh processing step. The MeshLab's "Screened Poisson Surface Reconstruction" feature, derived from the study by Kazhdan and Hoppe (2013), facilitated the creation of these meshes starting from their point clouds. Since MeshLab does not support by default the GLB format, the LODs were firstly imported into Blender and then exported as GLB files. Fig. 6 illustrates an example of the different exported LODs for one of the HDMs considered in the use case.

To achieve a visually appealing representation of the environment in VR, the IFC model exported from Revit was imported in Blender to define the UV coordinates and textures of the meshes. This process involved assigning textures derived from pictures taken during the on-site survey to their corresponding meshes. In Blender, UV mapping was performed to accurately align the textures with the 3D geometry (Figs. 7(a) and 7(b)). This involved using both the UV Unwrap method, where seams were manually defined to create more precise mappings, and the Smart UV Mapping feature for different meshes to achieve efficient and automated UV layouts. An example of a fully textured and UV mapped mesh is depicted in Fig. 7(c). Upon completion of the UV mapping, the textures and the UV data were exported locally, following the presented workflow, respectively as a set of PNG files and a JSON file.

Finally, the VR platform was employed to build the virtual visit based on the prepared data. The miniature of the HBIM model displayed in Fig. 8 shows the capability of the VR platform to successfully reconstruct the environment. The generated miniature offers users a preliminary overview, helping them understand the spatial layout and the POIs location before immersing themselves in the VE.

As it can be seen in Fig. 9, which illustrates the reconstructed VE during the virtual visit from different point of views, the VR platform was able to properly handle the graphics (e.g., materials and textures) and rendering features (e.g., reflections), as well as to identify the POIs defined within the HBIM model.

The POIs, placed at the floor level and displayed in blue in the figure, were equipped with a TP component, to allow the user to move from one POI to another, and a recognizable UI, so that they can be easily noted by the user.

As illustrated in Figs. 10 and 11, for each POI the platform activates associated LAOs, which are dynamically highlighted to focus the user's attention. In particular, Fig. 10 illustrates the first LAO of the first POI defined for the visit, highlighted with a spot light. Fig. 11 shows the UI panel that is displayed every time a LAO is activated. This enables the user to read textual descriptions as well as access multimedia contents like images and videos associated with the LAO, and listen to audio descriptions generated in real-time through TTS.

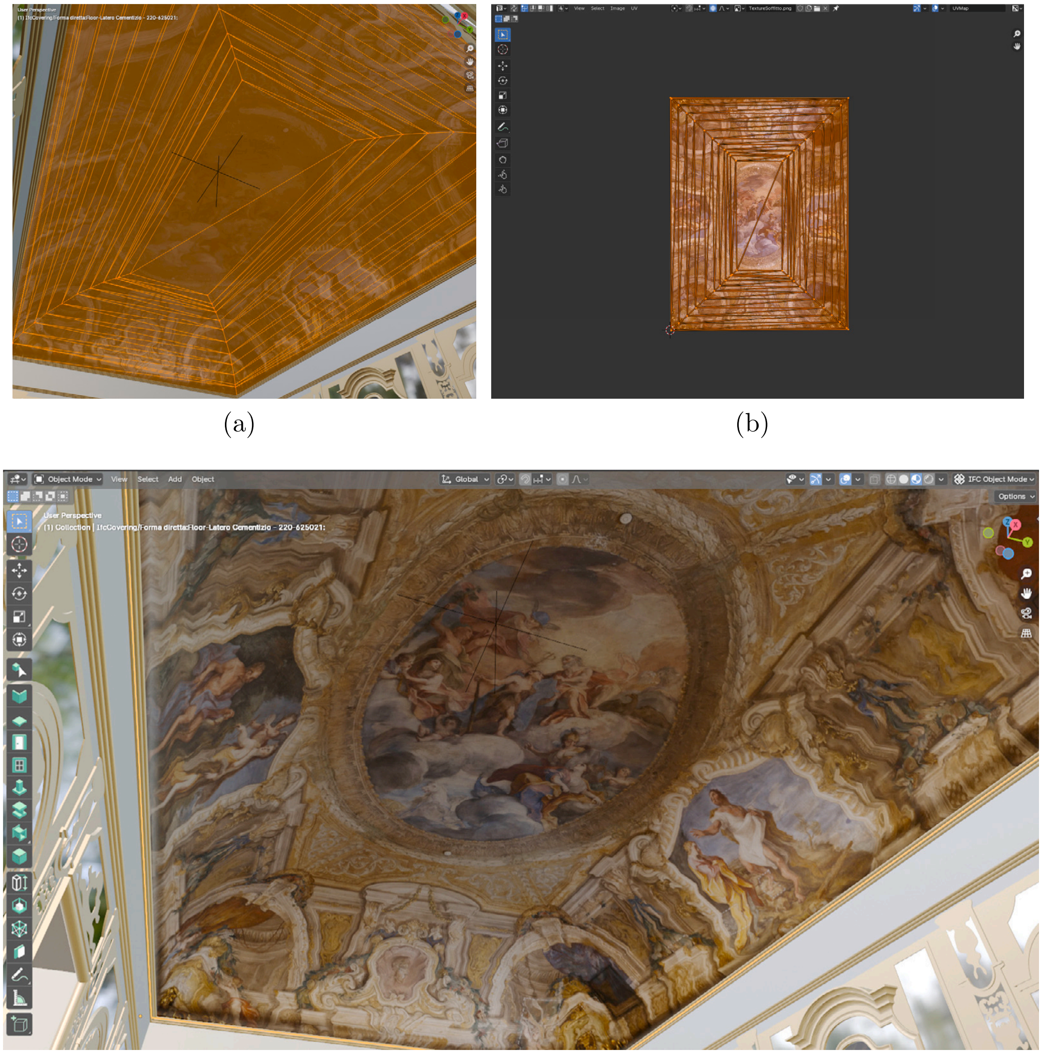
Fig. 6. Representation of the three LODs for one of the reconstructed decorations (the Winter season). For this example, the number of vertices obtained for each LOD was $\sim 260k$ (LOD0), $\sim 60k$ (LOD1), and $\sim 15k$ (LOD2).

5. Discussion and conclusions

This paper presents a novel semi-automated HBIM-to-VR workflow designed for developing VHEs using enriched IFC files and automated deployment through a VR platform. The workflow features two key phases. Firstly, the workflow involves a manual preparation phase that enriches the IFC file with additional external data, such as UV coordinates, textures, and HDMs. Secondly, it includes an automated deployment phase that manages environment reconstruction and facilitates the creation of a virtual visit using the developed VR platform.

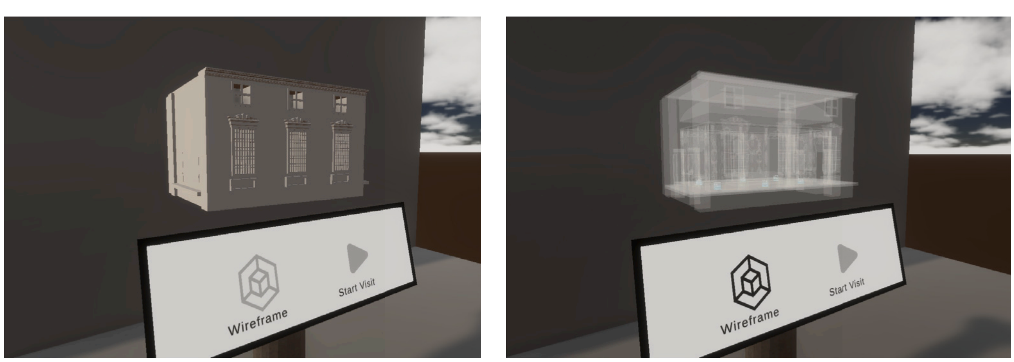
The workflow is applied to a real-world use case, i.e., the creation of a virtual visit based on the HBIM model of the "Hall of Seasons" at Palazzo Carignano, a notable historical site in Turin, Italy. The resulting VR application demonstrates the workflow's capability to generate immersive educational experiences from IFC files, thereby significantly improving the scalability and accessibility of CH valorization processes. In particular, the generated VR-based VHE incorporates key elements typical of traditional VHEs, such as teleportation through TPs and TAs, attention-guiding features, multimedia contents, and 3D models for both the VE and CH elements. Additionally, the VR application includes advanced graphics management capabilities, such as lighting and reflection control, and handles LODs for optimized performance. When comparing the features of the generated VHE to existing solutions in the state of the art, several distinctions emerge. Unlike most museum-integrated VHEs (Section 2.3), which require updates whenever there are changes to semantics or geometry, the VHE created by the proposed workflow leverages HBIM models. This approach allows for more efficient management and updating of data. Moreover, the VHE incorporates an audio guide powered by TTS technology, enabling dynamic updates to audio contents over time, whereas many other VHEs rely on static, pre-recorded audio. These features contribute to the scalability of the VHE, enabling both geometric and semantic data to be easily updated, and provide flexibility in creating auditory contents. It should also be noted that some configurations are not yet reproducible. For example, some VHEs, as discussed in Section 2.3, use 360° video to offer a realistic representation of cultural heritage sites but with limited interactivity. In contrast, other approaches (Puig et al., 2020; Restivo et al., 2023) utilize realistic 3D environments that enable interactive features, such as manipulation of virtual objects (e.g., artworks, remains). These additional features are part of the planned enhancements for the proposed workflow, with the aim to further advance its potential for generating any type of immersive VHEs.

Currently, the proposed workflow imposes some requirements in order to fully reconstruct a visually appealing environment from an HBIM model. At present, textures and UV data are not integrated directly within the IFC file, requiring the VR platform to retrieve them from external folders. Indeed, this aspect could be seen as a limitation by the users, since it requires them to perform manual operations using



(a) (b) (c)

Fig. 7. Frescoed vault texture visual representation and UV mapping (a–b) in Blender and (c) in the generated environment.



(a) (b)

Fig. 8. Miniature displayed at the end of the VE reconstruction displayed (a) using a flat gray material, and (b) in wireframe to enable the visualization of POIs.

Fig. 9. Visualization from different points of view of the VE during the virtual visit: (a) reconstruction of the environment and of its graphics and rendering features (e.g. mirror reflections), and examples of automatic management of textures and UV coordinates for (b) the frescoed vault and (c) other meshes.

additional tools (e.g., Blender). Nevertheless, current BIM platforms tend not to prioritize the support for this kind of contents, and this fact makes BIM-to VR workflows dependent from external modeling tools. Such limitation could be addressed by including in the workflow an extended IFC schema that includes comprehensive support for textures and UV data, integrating their metadata directly in the file.

Additional considerations should be made regarding the generated reflections and lighting. For reflections, the current VR platform calculates them based on the presence of one or more *IfcWall* elements, which can be limiting for open environments. As for lighting, it is currently calculated in real-time, which imposes restrictions on the number of lights that can be used in the environment due to performance constraints. A potential solution would be to pre-calculate the lighting by "baking" all the lights in the environment and converting this information into a "lightmap" that can be applied to the 3D models. Unfortunately, light baking is not available in Unity outside of the Editor, as it is particularly computationally intensive. Even if feasible, it would extend the application's startup time by tens of minutes, making it practically unfeasible. This limitation necessitates the use of external tools to pre-bake lightmaps for each 3D model before the application starts, or an intermediate baking step inside the Unity Editor. However, the proposed platform was intentionally designed to operate entirely at runtime, relying on Unity's real-time lighting, which may not be ideal for performance. That said, this approach offers several advantages. First, it eliminates the need to re-bake lights with every environment reconstruction. Second, it allows for handling dynamic VEs with varying lighting conditions. Third, avoiding an additional baking step simplifies the workflow, which is beneficial from an accessibility standpoint.

For what it pertains the positioning of the HDMs, at present the VR platform does not account for potential clipping with adjacent meshes, which could detract from the visual quality of the visualized models if the DMs are not accurately placed during the HBIM model creation. To mitigate this phenomenon, an automated collision detection and adjustment mechanism is planned to be incorporated in the future into the HDM positioning process.

Despite its current limitations, the proposed approach offers an additional purpose for BIM models beyond design and maintenance, focusing on the inclusion and accessibility of museum data. By semi-automating the HBIM-to-VR workflow and enriching IFC files with metadata, this approach significantly enhances the scalability of VHE creation. It not only facilitates the understanding and enjoyment of built heritage but also creates new opportunities for the enhancement

Fig. 10. First LAO assigned to the first POI defined for the virtual visit, highlighted through the activation of a spot light. In this case, the LAO is the decoration representing the Summer season.

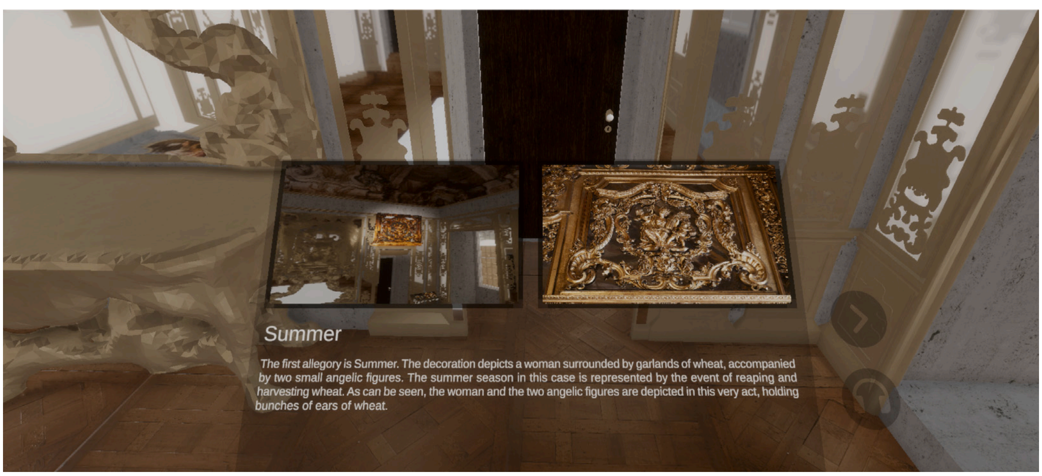


Fig. 11. UI panel displayed for the first LAO assigned to the first POI of the virtual visit, reporting cultural information directly gathered from the HBIM model.

and digital preservation of cultural assets. The potential of BIM models is vast, and their integration into VR experiences can make these experiences increasingly educational and interactive.

In this perspective, future advancements could include the simultaneous use of multiple models to illustrate how buildings have evolved over centuries. While this possibility presents additional challenges, such as ensuring accurate geolocation and correct model overlay, a well-configured IFC file setup could help to automate these processes in the creation of VHEs. Future work will also focus on adding support for generating VHEs in non-immersive VR, including the management of currently unconsidered elements like on-screen UIs and interaction via mouse clicks. Further experimentation with different HBIM models will also be conducted to validate the proposed workflow across various CH sites and VHEs. Moreover, additional functionalities could be incorporated, such as virtual object manipulation, accessibility features for users with physical or cognitive impairments, and technologies leveraging Large Language Models (Trichopoulos et al., 2023; Varitimiadis et al., 2021). It is also worth noting that, in its current implementation, data are accessed from local folders. However, the platform has been designed to facilitate the integration of a cloud-based retrieval system in future versions, enabling enhanced scalability and data accessibility.

Finally, testing with different user categories (both creating and using contents) will be conducted to gather feedback and enhance the usability and effectiveness of the workflow, ensuring that the generated VHEs are not only technically robust but also engaging and educational for diverse audiences.

CRediT authorship contribution statement

Jacopo Fiorenza: Writing – original draft, Software, Methodology, Investigation, Data curation, Conceptualization. **Nicola Rimella:** Writing – original draft, Methodology, Data curation, Conceptualization. **Davide Calandra:** Writing – review & editing, Writing – original draft, Supervision, Project administration. **Anna Osello:** Writing – original draft, Resources, Funding acquisition. **Fabrizio Lamberti:** Writing – review & editing, Writing – original draft, Supervision, Resources, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Achille, C., Lombardini, N., Tommasi, C., 2015. BIM and cultural heritage: Compatibility tests in an archaeological site. In: Proc. of International Conference on Building Information Modelling. BIM 2015, pp. 593–604. http://dx.doi.org/10.2495/BIM150481.

Alizadehsalehi, S., Hadavi, A., Huang, J., 2020. From BIM to extended reality in AEC industry. Autom. Constr. 116, 103254. http://dx.doi.org/10.1016/j.autcon.2020.103254.

Amigoni, F., Schiaffonati, V., 2009. The minerva system: A step toward automatically created virtual museums. Appl. Artif. Intell. 23, 204–232. http://dx.doi.org/10.1080/08839510802715159.

ArtPlacer, 2024. ArtPlacer. https://www.artplacer.com/. (Accessed: 28 October 2024).

Babalola, A., Musa, S., Akinlolu, M., Haupt, T., 2021. A bibliometric review of advances in building information modeling (BIM) research. J. Eng. Design Technol. 21, http://dx.doi.org/10.1108/JEDT-01-2021-0013.

Banfi, F., 2021. The evolution of interactivity, immersion and interoperability in HBIM: Digital model uses, VR and AR for built cultural heritage. ISPRS Int. J. Geo-Inf. 10 (10), http://dx.doi.org/10.3390/ijgi10100685.

Bayat, R., De Maio, E., Fiorenza, J., Migliorini, M., Lamberti, F., 2024. Exploring methodologies to create a unified VR user-experience in the field of virtual museum experiences. In: Proc. of 2024 IEEE Gaming, Entertainment, and Media Conference. GEM 2024, pp. 1–4. http://dx.doi.org/10.1109/GEM61861.2024.10585452.

Bianchini, C., Potestà, G., 2021. BIM for built cultural heritage: Semantic segmentation, architectural stratification and LOD of the baptistery of san giovanni in florence. In: Bolognesi, C., Villa, D. (Eds.), From Building Information Modelling To Mixed Reality. Springer International Publishing, Cham, pp. 1–15. http://dx.doi.org/10.1007/978-3-030-49278-6.

Bolognesi, C., Fiorillo, F., 2023. Virtual representations of cultural heritage: Sharable and implementable case study to be enjoyed and maintained by the community. Buildings 13 (2), http://dx.doi.org/10.3390/buildings13020410.

Building Smart, 2010a. Industry foundation classes (IFC). https://technical.buildingsmart.org/standards/ifc/. (Accessed: 23 August 2024).

Building Smart, 2010b. openBIM. https://www.buildingsmart.org/about/openbim/. (Accessed: 05 August 2024).

BuildingSmart, 2020a. IfcTextureMap. https://ifc43-docs.standards.buildingsmart.org/IFC/RELEASE/IFC4x3/HTML/lexical/IfcTextureMap.htm. (Accessed: 05 August 2024).

BuildingSmart, 2020b. Model view definition. https://technical.buildingsmart.org/standards/ifc/mvd/. (Accessed: 23-August-2024).

Calandra, D., Lamberti, F., 2024. A testbed for studying cybersickness and its mitigation in immersive virtual reality. IEEE Trans. Vis. Comput. Graphics 1–18. http://dx.doi.org/10.1109/TVCG.2024.3448203.

Cannavó, A., Calandra, D., Pratticó, F.G., Gatteschi, V., Lamberti, F., 2021. An evaluation testbed for locomotion in virtual reality. IEEE Trans. Vis. Comput. Graphics 27 (3), 1871–1889. http://dx.doi.org/10.1109/TVCG.2020.3032440.

Cerri, M.G., 1990. Palazzo Carignano: Tre secoli di idee, progetti e realizzazioni. Umberto Allemandi, p. 262.

Chen, H., Hale, J., Hanks, L., 2024. Archive or exhibition?: A comparative case study of the real and virtual Pitt Rivers Museum. Dig. Appl. Archaeol. Cultural Heritage 32, e00305. http://dx.doi.org/10.1016/j.daach.2023.e00305.

Dataverse Ltd, 2024. Artsteps. https://www.artsteps.com/. (Accessed: 27 October 2024).

Duque Mahecha, S., Aguacil Moreno, S., Stoll, A.D., De Sousa Pereira, S., Deschamps, L., 2021. Texture mapping and IFC material retrievement for virtual reality applications. In: Proc. of Building Simulation 2021: 17th Conference of IBPSA, Vol. 17. BS2021, pp. 3129–3135. http://dx.doi.org/10.26868/25222708.2021.30541.

European Committee for Standardization, 2024. EN ISO 7817-1:2024: Building information modelling - level of information need - part 1 concepts and principles (ISO 7817-1:2024). European Standard.

Ferretti, U., Quattrini, R., D'Alessio, M., 2022. A comprehensive HBIM to XR framework for museum management and user experience in ducal palace at urbino. Heritage 5 (3), 1551–1571. http://dx.doi.org/10.3390/heritage5030081.

Giangreco, I., Sauter, L., Parian, M., Gasser, R., Heller, S., Rossetto, L., Schuldt, H., 2019. VIRTUE: A virtual reality museum experience. In: Companion Proc. of 24th International Conference on Intelligent User Interfaces. IUI '19 Companion, pp. 119–120. http://dx.doi.org/10.1145/3308557.3308706.

Goto, K., Kotani, M., Toyama, M., 2018. 3D virtual museum generation by using SuperSQL. Int. J. Pervasive Comput. Commun. 14 (2), 124–146. http://dx.doi.org/10.1108/IJPCC-D-18-00026.

Graham, K., Chow, L., Fai, S., 2019. From BIM to VR: Defining a level of detail to guide virtual reality narratives. J. Inf. Technol. Construct. 24, 553–568. http://dx.doi.org/10.36680/j.itcon.2019.031.

Hanson, D., 2024. New Art City. https://newart.city/. (Accessed: 27 October 2024).

Hayashi, M., Bachelder, S., Nakajima, M., 2020. Automatic generation of art exhibitions from the internet resources. In: Proc. of 2020 IEEE 9th Global Conference on Consumer Electronics. GCCE 2020, pp. 642–643. http://dx.doi.org/10.1109/GCCE50665.2020.9291722.

IfcOpenShell, 2022. IfcConvert. https://docs.ifcopenshell.org/ifcconvert.html. (Accessed: 02 August 2024).

International Organization for Standardization, 2024. ISO/TS 16739-1:2024 Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries. Edition 2.

Jevremovic, V., Fuerer, A., 2024. VR-All-Art. https://vrallart.com/. (Accessed: 27 October 2024).

Jung, T., tom Dieck, M.C., Lee, H., Chung, N., 2016. Effects of virtual reality and augmented reality on visitor experiences in museum. In: Inversini, A., Schegg, R. (Eds.), Proc. of Information and Communication Technologies in Tourism 2016. pp. 621–635. http://dx.doi.org/10.1007/978-3-319-28231-2_45.

Kamari, A., Paari, A., Torvund, H., 2021. BIM-enabled virtual reality (VR) for sustainability life cycle and cost assessment. Sustainability 13 (1), http://dx.doi.org/10.3390/su13010249.

Kazhdan, M., Hoppe, H., 2013. Screened poisson surface reconstruction. ACM Trans. Graph. 32 (3), http://dx.doi.org/10.1145/2487228.2487237.

Khorchi, A., Boton, C., 2024. An OpenBIM-based 4D approach to support coordination meetings in virtual reality environments. J. Build. Eng. 85, 108647. http://dx.doi.org/10.1016/j.jobe.2024.108647.

Kim, H., Shakeri, M., Shin, J.-E., Woo, W., 2024. Space-adaptive artwork placement based on content similarities for curating thematic spaces in a virtual museum. ACM J. Comput. Cultural Heritage 17 (1), http://dx.doi.org/10.1145/3631134.

Kiourt, C., Koutsoudis, A., Pavlidis, G., 2016. DynaMus: A fully dynamic 3D virtual museum framework. J. Cultural Heritage 22, 984–991. http://dx.doi.org/10.1016/j.culher.2016.06.007.

Korkut, E., Surer, E., 2024. Developing a framework for heterotopias as discursive playgrounds: A comparative analysis of non-immersive and immersive technologies. Virtual Real. 28 (1), 16. http://dx.doi.org/10.1007/s10055-023-00905-w.

Kunstmatrix, 2024. Kunstmatrix. https://www.kunstmatrix.com/en. (Accessed: 27 October 2024).

Louvre Museum, 2019. Mona Lisa Beyond the Glass. https://www.louvre.fr/en/explore/life-at-the-museum/mona-lisa-beyond-the-glass-the-louvre-s-first-virtual-reality-experience. (Accessed: 5 November 2024).

Lovell, L., Davies, R., Hunt, D., 2023. The application of historic building information modelling (HBIM) to cultural heritage: A review. Heritage 6 (10), 6691–6717. http://dx.doi.org/10.3390/heritage6100350.

Lu, H., Ren, H., Feng, Y., Wang, S., Ma, S., Gao, W., 2021. GazeTance guidance: Gaze and distance-based content presentation for virtual museum. In: 2021 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops. VRW, pp. 462–463. http://dx.doi.org/10.1109/VRW52623.2021.00113.

Lucchi, E., 2023. Digital twins for the automation of the heritage construction sector. Autom. Constr. 156, 105073. http://dx.doi.org/10.1016/j.autcon.2023.105073.

Meinecke, C., Hall, C., Jänicke, S., 2022. Towards enhancing virtual museums by contextualizing art through interactive visualizations. J. Comput. Cultural Heritage 15 (4), http://dx.doi.org/10.1145/3527619.

Murphy, M., McGovern, E., Pavia, S., 2009. Historic building information modelling (HBIM). Struct. Survey 27 (4), 311–327. http://dx.doi.org/10.1108/02630800910985108.

Natephra, W., Motamedi, A., Fukuda, T., Yabuki, N., 2017. Integrating building information modeling and virtual reality development engines for building indoor lighting design. Visualiz. Eng. 5 (1), 19. http://dx.doi.org/10.1186/s40327-017-0058-x.

National BIM Standard Project Committee, et al., 2007. National building information modeling standard, version 1, Part 1: Overview, principles, and methodologies. National Institutute of Building Sciences.

Oostwegel, L.J.N., Jaud, Š., Muhič, S., Malovrh Rebec, K., 2022. Digitalization of culturally significant buildings: Ensuring high-quality data exchanges in the heritage domain using OpenBIM. Heritage Sci. 10 (1), 10. http://dx.doi.org/10.1186/s40494-021-00640-y.

Oumoumen, K., Aboubane, F., Younes, E.-C., 2024. Automation of historical buildings: Historical building information modeling (HBIM) based virtual reality (VR). In: Proc. of 10th International Meeting on Mediterranean Architectural Heritage (RIPAM10), Vol. 40. pp. 319–322. http://dx.doi.org/10.21741/9781644903117-34.

Paolanti, M., Puggioni, M., Frontoni, E., Giannandrea, L., Pierdicca, R., 2023. Evaluating learning outcomes of virtual reality applications in education: A proposal for digital cultural heritage. J. Comput. Cultural Heritage 16 (2), 1–25. http://dx.doi.org/10.1145/3593432.

Penjor, T., Banihashemi, S., Hajirasouli, A., Golzad, H., 2024. Heritage building information modelling (HBIM) for heritage conservation: Framework of challenges, gaps, and existing limitations of HBIM. Digital Appl. Archaeol. Cultural Heritage e00366. http://dx.doi.org/10.1016/j.daach.2024.e00366.

Preloaded, 2021. Curious alice: The VR experience. https://preloaded.com/work/curious-alice/. (Accessed: 5 November 2024).

Puig, A., Rodríguez, I., Arcos, J.L., Rodríguez-Aguilar, J.A., Cebrián, S., Bogdanovych, A., Morera, N., Palomo, A., Piqué, R., 2020. Lessons learned from supplementing archaeological museum exhibitions with virtual reality. Virtual Real. 24 (2), 343–358. http://dx.doi.org/10.1007/s10055-019-00391-z.

Pybus, C., Graham, K., Doherty, J., Arellano Risopatron, N., Fai, S., 2019. New realities for canada's parliament: A workflow for preparing heritage bim for game engines and virtual reality. In: ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, vol. XLII-2/W15. pp. 945–952. http://dx.doi.org/10.5194/isprs-archives-XLII-2-W15-945-2019.

Restivo, S., Cannavó, A., Terzoli, M., Mezzino, D., Spallone, R., Lamberti, F., 2023. Interacting with Ancient Egypt Remains in High-Fidelity Virtual Reality Experiences. In: Bucciero, A., Fanini, B., Graf, H., Pescarin, S., Rizvic, S. (Eds.), Proc. of Eurographics Workshop on Graphics and Cultural Heritage. The Eurographics Association, http://dx.doi.org/10.2312/gch.20231175.

Rimella, N., Del Giudice, M., Ugliotti, F.M., Tarantola, G., Osello, A., 2023. Matrice delle transizioni nell'ambito disciplinare del disegno. In: 44° Convegno Internazionale della Unione Italiana per il Disegno. pp. 1197–1210. http://dx.doi.org/10.3280/oa-1016-c3443.

Selmanoviĉ, E., Rizvic, S., Harvey, C., Boskovic, D., Hulusic, V., Chahin, M., Sljivo, S., 2020. Improving accessibility to intangible cultural heritage preservation using virtual reality. J. Comput. Cultural Heritage 13 (2), 1–19. http://dx.doi.org/10.1145/3377143.

Shahab, H., Mohtar, M., Ghazali, E., Rauschnabel, P.A., Geipel, A., 2023. Virtual reality in museums: Does it promote visitor enjoyment and learning? Int. J. Human–Comput. Interact. 39 (18), 3586–3603. http://dx.doi.org/10.1080/10447318.2022.2099399.

Skublewska-Paszkowska, M., Milosz, M., Powroznik, P., Lukasik, E., 2022. 3D technologies for intangible cultural heritage preservation—literature review for selected databases. Heritage Sci. 10 (1), 1–24. http://dx.doi.org/10.1186/s40494-021-00633-x.

Smithsonian American Art Museum, 2018. Beyond the Walls. https://americanart.si.edu/beyond-the-walls. (Accessed: 5 November 2024).

Spallone, R., Lamberti, F., Auenmüller, J., Calandra, D., Fasano, F., Rinascimento, M., 2024a. Immersive experiences for the re-contextualization of statues of the goddess sekhmet. In: Giordano, A., Russo, M., Spallone, R. (Eds.), Advances in Representation: New AI- and XR-Driven Transdisciplinarity. Springer Nature Switzerland, Cham, pp. 141–159. http://dx.doi.org/10.1007/978-3-031-62963-1_9.

Spallone, R., Lamberti, F., Vigo, L., Ronco, F., Calandra, D., Ferraro, M., 2024b. 3Dmodelling and virtual reality for museum heritage presentation: Contextualisation of sculpture from the Tang era. Int. Arch. Photogram. Remote Sens. Spatial Inf. Sci. XLVIII-2/W4-2024, 413–420. http://dx.doi.org/10.5194/isprs-archives-XLVIII-2-W4-2024-413-2024.

Suhari, K., Saptari, A., Abidin, H., Gunawan, P., Meilano, I., Hernandi, A., Widyastuti, R., 2024. Exploring BIM-based queries for retrieving cultural heritage semantic data. http://dx.doi.org/10.21203/rs.3.rs-3812967/v1, PREPRINT (Version 1) available at Research Square.

Sylaiou, S., Dafiotis, P., Koukopoulos, D., Koukoulis, K., Vital, R., Antoniou, A., Fidas, C., 2024. From physical to virtual art exhibitions and beyond: Survey and some issues for consideration for the metaverse. J. Cultural Heritage 66, 86–98. http://dx.doi.org/10.1016/j.culher.2023.11.002.

The Kremer Collection, 2017. The Kremer Museum. https://thekremercollection.com/. (Accessed: 5 November 2024).

Trichopoulos, G., Konstantakis, M., Caridakis, G., Katifori, A., Koukouli, M., 2023. Crafting a museum guide using ChatGPT4. Big Data Cognit. Comput. 7 (3), http://dx.doi.org/10.3390/bdcc7030148.

Unity Technologies, 2023. Unity glTFast Documentation. https://docs.unity3d.com/Packages/com.unity.cloud.gltfast@5.2/manual/index.html. (Accessed: 02 August 2024).

van Nederveen, G., Tolman, F., 1992. Modelling multiple views on buildings. Autom. Constr. 1 (3), 215–224. http://dx.doi.org/10.1016/0926-5805(92)90014-B.

Varitimiadis, S., Kotis, K., Pittou, D., Konstantakis, G., 2021. Graph-based conversational AI: Towards a distributed and collaborative multi-chatbot approach for museums. Appl. Sci. 11 (19), http://dx.doi.org/10.3390/app11199160.

Vital, R., Sylaiou, S., Koukopoulos, D., Koukoulis, K., Dafiotis, P., Fidas, C., 2023. Comparison of extended reality platforms and tools for viewing and exhibiting art. Digital Appl. Archaeol. Cultural Heritage 31, e00298. http://dx.doi.org/10.1016/j.daach.2023.e00298.

Wagner, B., Kramer, J., Wenzel, M., 2021. LINQ to XML overview. https://learn.microsoft.com/en-us/dotnet/standard/linq/linq-xml-overview. (Accessed: 05 August 2024).

Wong, J.-Y., Chun Chieh, Y., Yong, S.-T., Chan, A., Kok, S.-T., Lau, T., Ali, M., Gouda, E., 2020. BIM-VR framework for building information modelling in engineering education. Int. J. Interact. Mob. Technol. (IJIM) 14, 15. http://dx.doi.org/10.3991/ijim.v14i06.1339.

Zidianakis, E., Partarakis, N., Ntoa, S., Dimopoulos, A., Kopidaki, S., Ntagianta, A., Ntafotis, E., Xhako, A., Pervolarakis, Z., Kontaki, E., Zidianaki, I., Michelakis, A., Foukarakis, M., Stephanidis, C., 2021. The invisible museum: A user-centric platform for creating virtual 3D exhibitions with VR support. Electronics 10 (3), http://dx.doi.org/10.3390/electronics10030363.