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BIM-to-VR for Museums: A Multilayered Representation for Integrated Access and Management of Buildings and Collections

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Abstract

Museum building information modeling is an emerging research field that harnesses the potential of digitization applied to both architecture and artworks. This present work aims to innovate the current practices by integrating virtual tours and semantic-aware models while also fostering the uses of the informed models beyond management or professional use. The methodology consists of a 3D informed model able to manage the collection catalog, leveraging the BIM paradigm. Subsequently, a VR desktop tool is developed based on panoramic images fully interoperable with data enrichment and all the informative layers. The results demonstrate the feasibility of a workflow for a multilayer platform for museums that balances computational issues and ensures correct representation of various levels of geometry and information. The assessment in a real-world scenario through a fully operative prototype of museum BIM to VR also allows us to outline perspectives for dissemination purposes.

Keywords: MBIM; scan to BIM; BIM to VR; digital transition; multilayered platform; museum

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1. Introduction

The digital transformation of cultural heritage (CH) is a multifaceted scenario that asks for innovative research and cross-fertilization of skills and disciplines [1]. The digitization of artworks and their online dissemination are increasingly acknowledged as pivotal tools to foster communication, support conservation, and enable smart and sustainable management. In addition, a significant advantage lies in the possibility of creating a digital twin of the building that houses the collection, through Heritage Building Information Modeling (HBIM). This approach provides not only geometry, but also a huge amount and type of information inherited and coherent with the 3D representation. Moreover, this methodology requires a single point of access for all the information available, avoiding fragmentation or loss of data over time.

However, especially if the museum is hosted in a historic building, the heterogeneity of information and geometric complexity can make it difficult to obtain a model with a high LOG (Level of Geometry) without investing considerable resources. Consequently, similar tasks affect the entire modeling process, causing its low diffusion and unsustainability, both in terms of time and cost.

This work is inserted in research actions that enable all museums, including small and medium-sized ones, to benefit from digital transformation. Creating a seamless and effective workflow from HBIM to VR poses significant technical, methodological, and practical challenges. Therefore, this research aims to address these challenges by developing a comprehensive and integrated workflow that facilitates the transition from informed models to embodied experiences specifically tailored for the management of museum collections and CH spaces. The key objectives of similar approaches are to promote solutions which make CH accessible and its management effective, leveraging the use of advanced digital platforms and exploiting the Digital Twin concept.

For such purposes, the case study is the Civic Art Gallery of Ascoli Piceno, located in the Palazzo dell'Arengo. The collection occupies the first and second floors of the historical building; its key feature is that the exhibited works cannot be detached from the building. Every piece of furniture, showcase, and even the tapestry and fixed furnishings help to create a unitary itinerary together with the collection. Such consideration makes it even more challenging the task to carry out an HBIM for the present case study, asking for different innovative solutions.

Thus, the research approach was stimulated by the idea of building up an architectural 3D informed model able to also manage the collection catalog, exploiting the BIM paradigm and the visual effectiveness of panoramas. The final output is conceived as a VR desktop tool in which a Museum BIM (MBIM) and its data enrichment are interoperable and linked with a Virtual Tour (VT): this way the user can browse and query all management info while navigating in a highly detailed environment.

The BIM methodology is widely used in the architecture, engineering, and construction (AEC) industry. It facilitates collaboration among different stakeholders and allows for real-time sharing of information, reducing errors and miscommunication [1]. Indeed, BIM integrates various types of data, including architectural, structural, and MEP information [2]. Moreover, several European countries have adopted policies and initiatives to promote the adoption of BIM within the construction and infrastructure sectors [3]. The goal of these policies is to establish a standardized framework for the use of BIM across the industry, ensuring that all stakeholders involved in construction projects can work with a common reference.

Over ten years ago, the BIM methodology started to be applied to existing buildings [4], giving rise to a new action line commonly referred to as Heritage BIM [5]. Indeed, the BIM approach has a positive impact throughout the building lifecycle that includes the design and construction phases, but also maintenance and decommissioning, renewal, and updating interventions [6].

When it comes to historical buildings, there are significant challenges related to material and constructive consistency, which must be largely reconstructed only by their exterior characteristics, resulting in many uncertainties [7]. So, many HBIM studies stressed BIM tools to provide a documentation of historical buildings, monuments, and cultural heritage sites able to support their preservation, providing detailed digital representations which not only refer to their three-dimensional characterization [8]. Indeed, an HBIM model can be considered as a database that incorporates 3D geometric representation, historical data, construction methods, materials, and other relevant information to provide a comprehensive understanding of the building's history and condition [9]. Once a historical building is documented using HBIM methodology, the virtual model can support planning and executing conservation projects [10–12], and it can be used for structural analysis, environmental simulations, and other assessments to understand how the building structures may be affected by aging, weather, and potential interventions [13,14].

Another relevant aspect of the HBIM approach is the possibility of disseminating content by combining visual data and information [15]. Consequently, combined with XR technologies, HBIM enables innovative solutions to access data related to both professional and educational domains [16,17].

1.1. BIM Methodology for Museum Buildings and Collections

Particularly in Italy and Europe, most of the museums are hosted in historical buildings. So, several studies on HBIM methodology broadened their field of application to the integrated management of museum buildings and their collections. Reference [18] uses simplified geometric volumes to represent the archeological artifacts on display within the HBIM of the National Archaeological Museum of the Marche Region. By linking the 3D objects to an external database, the BIM model becomes semantically enriched. So, each geometric representation (e.g., a cylinder) acts as a visual anchor for accessing a wealth of information about the associated archeological artifact. In [19], the creation of semantically enriched 3D models known as Collection Information Models (CIMs) represents a significant advancement in the application of BIM within the museum context. Particularly, the study emphasizes the potential in recording within the BIM environment the relationship between container (the museum building) and contents (the artifacts on display) to enhance curatorial capabilities. Reference [20] presents a holistic information management system for the Galleria dell'Accademia di Firenze, a noteworthy example of the application of BIM principles to enhance the management and experience of artworks within a museum. In [21], families with high Level Of Detail (LOD) and high Level Of Information (LOI) are exploited to develop tools supporting managers and museum curators while enabling immersive and interactive cultural experiences. Finally, in the study of the relationship between buildings and artworks, although it does not explicitly refer to BIM-based modeling, [22] is particularly relevant as it proposes a formal approach to the semantic representation of the relationships between objects and spaces, leading to the definition of an ontology capable of linking artworks to specific wall surfaces within exhibition rooms and tracing their spatial provenance over time.

1.2. Multilayered Documentation of Cultural Heritage

Concerning the geometric and information complexity that BIM models can achieve, different definitions have been created: Level of Detail, Level of Development, and Level of Definition. Nevertheless, a generalized consensus has been established as regards the definition of a sequence of five levels of development: LOD100, LOD200, LOD300, LOD400, and LOD500, in accordance with the proposal of the American Institute of Architects. In Italy, the UNI 11337 divided LOD into Level Of Geometry (LOG) and Level Of Information (LOI) and defined seven specific levels to classify BIM models: from A to E for architectural drawing and F and G for as-built representations (UNI 11337-4:2017) [23].

In [24], the concept of GoG (Grade of Generation) protocols is introduced to describe different Levels of Geometry (LOG) in function of the geometry resulting from the laser scans, in the line of traditional Level of Detail (LOD) to the case of architectural heritage restoration. This reflection is upgraded and validated by the already mentioned UNI's definition. Focusing on the scan-to-BIM process, it allows for accurate modeling and visualization of as-built conditions [25]. Other works focused on the creation of ontologies as a valuable base for possible upgrading of what is expected/required in HBIM, especially considering the valuable goal of dissemination [26]. Hence, to reach a high geometric accuracy, HBIM workflow often relies on 3D surveys that are carried out integrating geomatics techniques, i.e., laser scanning and photogrammetry [27]. But although data-capturing tools are becoming more and more efficient, the scan-to-BIM process is still a non-automatic workflow, and creating visually detailed parametric models of complex historical buildings is still challenging and time-consuming [28]. It is underlined in the literature that the need for automation is crucial to balance the clear benefits of digitization against the costs of digital upskilling or further interdisciplinary recruitment [29].

Moreover, HBIM models are not always effective for applications demanding a high level of visual accuracy. Triggered by the current lack of an HBIM approach capable of creating models with both high geometric accuracy and high semantic richness, [30] presented a platform for multilayered documentation of CH that can include data of different types, such as a point cloud, textured polygonal mesh, parametric information model, and images, both 2D images and 360° panoramas. Focusing on CH preservation, the challenge of sharing and interacting with heterogeneous datasets has been addressed using different solutions. Reference [31] presents the web-based platform BIM3DSG. It enables the visualization and use of 3D models and survey data (as point clouds), which are linked to a database storing different types of information. The database can be regularly updated to monitor the conservation state and eventually support an intervention of conservation. Reference [32] presents two experiences about information systems and integrated services platforms for managing CH. An information system for the restoration of the Neptune's Fountain, an efficient and user-friendly tool for the management of the entire process of collection, preservation, and retrieval of data and related information from the early diagnostic and planning phase to the actual intervention step, and the SACHER 3D Life Cycle Management for CH service, an open-source and federated cloud computing-based platform able to support the complete life cycle management of various kinds of data concerning cultural assets.

1.3. Research Aims

Within this framework and considering the achievements of the different approaches, the research presented here aims to create and test a data collector, i.e., a data management system for the facility management of a museum (Figure 1).

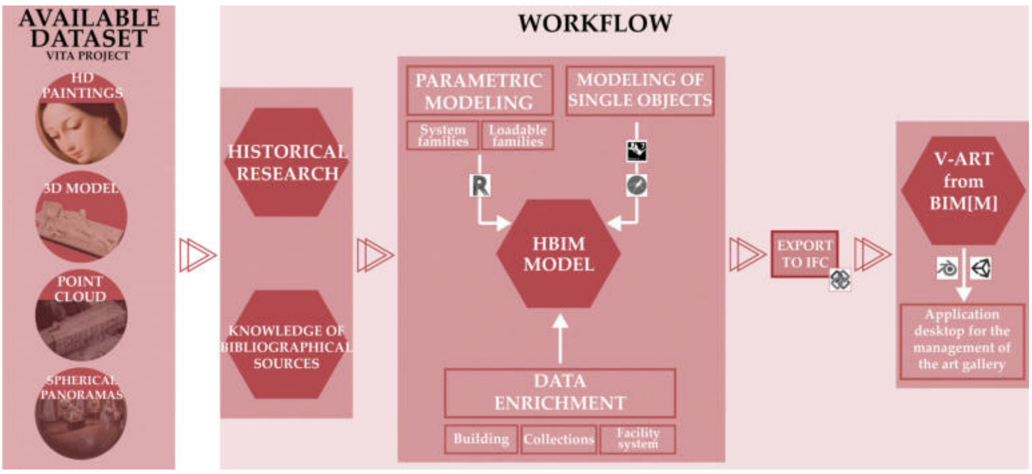


Figure 1. Methodological framework.

The art gallery is considered a built complex that encompasses both the architectural space and all the related information, thus including the different kinds of artwork here displayed, such as paintings, sculptures, and antique furniture. So, the proposed BIM process, the data enrichment, the pairing and synchronization with an immersive VT, as well as the subsequent features enabled within a VR tool, are designed to assess and stress a workflow facilitating the management of both collections and buildings. Therefore, the development of all contents and interactions started from the assumption that the gallery, intended as a container, and the collections that it holds are closely related.

The research ambitions are twofold. On the one hand, the goal is to stress the HBIM process to generate a geometric and informed model for a specific museum use case, focusing on its interoperability and sustainability aspects. The concept of interoperability pertains to the seamless integration of diverse data sources and databases, transcending disciplinary boundaries, thereby enabling the consolidation of disparate elements and information within a unified project framework. In addition, this approach must be sustainable, avoiding data duplication and supporting their reuse at a later time, even if aimed at visualization considering the current stage. Therefore, the main aim of this research is to optimize the HBIM workflow by integrating a simplified HBIM (low level of geometry—LOG) with a heterogeneous dataset from previous digitization, taking advantage of a game engine to deepen the research on BIM for museums by holding together the management needs of the building and of the artworks on display, along with the experience of cultural content.

2. Materials and Methods

2.1. Case Study

The Civic Art Gallery of Ascoli Piceno is located on the first and second floors of the Palazzo dell'Arengo, situated in the town center, overlooking one of the main squares: Piazza Arringo, also known as Piazza dell'Arengo, due to the popular assemblies originally held there (Figure 2).

Figure 2. Exterior facade of the Arengo Palace and view of the exhibition area on the first floor.

The current building has undergone several transformations over the centuries, primarily due to different owners and intended uses. The earliest traces of this palace date back to the second half of the 13th century [33]. Whereas the most significant restoration was carried out between the years 1679 and 1745 by Giuseppe and Antonio Giosaffatti. During this period, the facade of the building was transformed using the typical local travertine. The ground floor was enriched with an imposing portico, while the two upper floors were adorned with windows decorated with male and female caryatids, proving the artistic expertise of the Giosaffatti brothers.

In 1861, the Civic Art Gallery was established here, housing a valuable collection of paintings and other forms of artwork from the several churches and convents in the town. Currently, the collection hosts 800 exhibited objects, including a wide range of paintings, sculptures, and decorative art objects spanning from the Middle Ages to the 19th century; an eclectic collection encompassing works both by local and international artists.

In 2021, the V.I.T.A. (Virtual Immersion in Territorial Arts) Project was launched by the cooperatives of the "Il Picchio" consortium and the research group Distori Heritage of the Polytechnic University of the Marche Region. The project was financed by the Marche Region (Por-Fesr 2014–2020 funds) with the main objective of digitizing the most significant cultural institutions in the city, including the Civic Art Gallery of Ascoli [34].

The very first output of this project was a point cloud of the Arengo Palace representing both the exteriors and interiors of the Civic Art Gallery. Laser scanner acquisition of the exterior of the Arengo Palace and its roof, obtained by drone photogrammetry, generated a discrete model (point cloud) of the building. The two levels of the interior of the Pinacoteca Civica were then linked to it and georeferenced. Table 1 summarizes the main data about the survey campaign.

Table 1. TLS and UAV data.

TLS Data	Photogrammetric Data
No. of stations: 84	No. of images: 150
Scanning resolution: 6.3 mm @ 10 m	Image resolution: 4000 × 3000 px
Total no. of points > 11 bln	Total no. of points: 80 mln
Max alignment error: 13 mm	Total alignment error: 36 mm

Furthermore, textured 3D digital replicas of selected artworks, gigapixels of some paintings, and high-resolution spherical panoramas have been acquired and processed. The virtual museum of the Ascoli Civic Art Gallery was obtained by implementing a huge database consisting of 84 panoramas, 4 gigapixel images, short and extended captions, and some 3D models plus the director interviews [35]. The results obtained within the VITA Project represent the basis for the implementation of the methodology presented in this paper.

2.2. Scan-to-HBIM

Taking advantage of the data acquired by laser scanning the Palazzo dell'Arengo, a scan-to-BIM methodology was adopted to generate an HBIM model. Consequently, a semantic ontology was developed to manage suitable geometries (LOG) and information layers (LOI), achieving a C Level of Development (LOD) for the collections and E LOD for the building, in compliance with UNI 11337 regulations. The first step involved the pre-processing of the point cloud of Palazzo dell'Arengo, encompassing both interior and exterior spaces. Firstly, the point cloud was decimated according to a regular subsample, setting the minimum distance between points to 3 mm. Then, the resulting point cloud was segmented into seven parts according to the building's internal layout. The described process of decimation and segmentation was carried out within the Leica Cyclone 3DR 2023.0.1.42806 software. Each part of the point cloud was separately imported into the BIM authoring software Autodesk Revit 2022, providing an accurate reference for modeling the current condition of the building (Figure 3).

The semantic structure of the model was based on the standard data organization of the software, using existing families and extending them with custom types specifically created to represent the distinctive features of the building and its artworks; moreover, specifying the IfcExportAS and IfcExportType parameters to ensure their correct assignment during the IFC export process (Tables 1 and 2).

Walls, floors, and stairs were directly modeled on the point cloud, trying to respect the main geometries and with specific modeling procedures in place. Challenges arose due to out-of-plumb walls, considering that the wall objects in Revit are strictly perpendicular to the floors. In this case, considering that the focus of the modeling procedure was out of the structural analysis, this irregularity was omitted. On the other hand, for elements like windows, doors, frames, and unique features such as the large, glazed entrance compass, fireplace, and travertine niche, parametric families were created through "parametric object-oriented modeling". These objects were conceptualized into their generative matrices, from which we created the "source families", declined into their variations and adaptations in the HBIM model according to the different measures visible in the point clouds (Figure 4).

External decorations and aedicule windows of the palace were also modeled, implementing all the geometrical parameters.

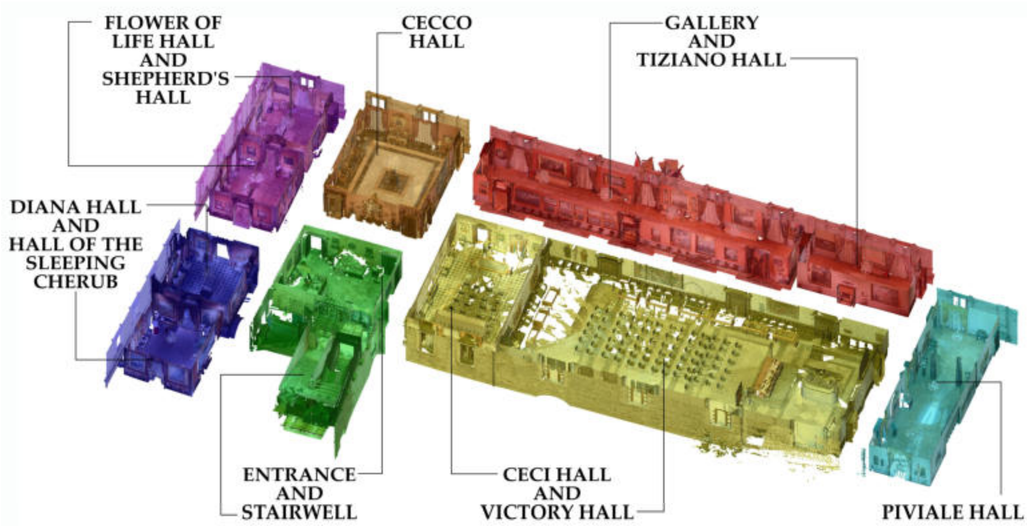


Figure 3. Segmentation of the point cloud of the main floor of the Arengo Palace.

Table 2. Building elements and artworks and related IFC classes.

Building Element/Artwork	IFC Class (Type)
Building complex	IfcBuilding (COMPLEX)
Building unit	IfcBuilding (PARTIAL)
Building level	IfcBuildingStorey
Exhibition room	IfcSpace (ROOM)
Wall	IfcWall
Column	IfcColumn
Window	IfcWindow
Door	IfcDoor
Molding	IfcCovering (MOULDING)
Stair	IfcStair (HALFTURN_STAIR)
Flooring	IfcCovering (FLOORING)
Vault	IfcSlab
Artwork	IfcFurnishingElement (PAINTING/STATUE)
Furniture	IfcFurniture (CHAIR/TABLE)
Sensor	IfcSensor (MOVEMENTSENSOR)
Camera	IfcAudioVisualAppliance (CAMERA)

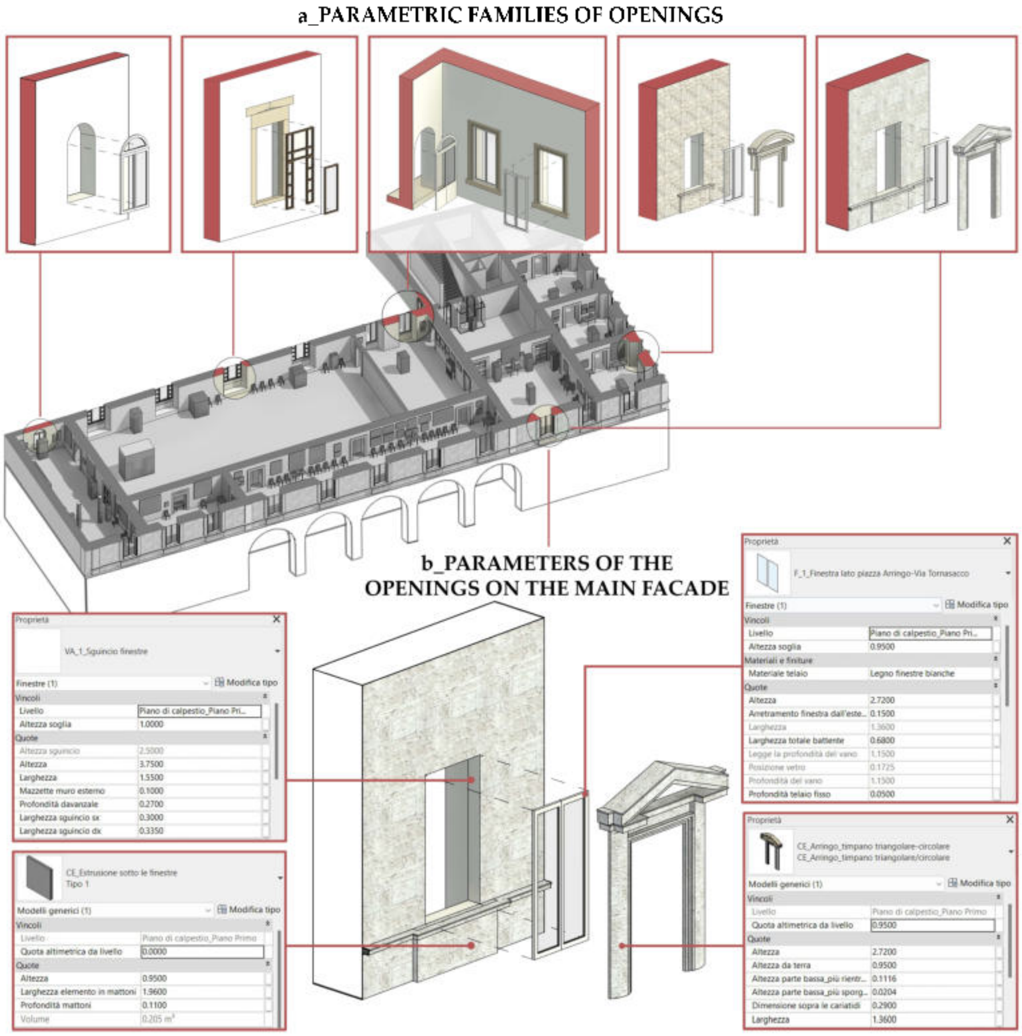


Figure 4. Parametric definition of the window family in Revit, with geometric parameters (e.g., height, depth) specified through the properties panel.

Moreover, each gallery room is covered by vaulted ceilings, whose modeling was differently managed according to its geometry. For simple vaults, adaptive families with four points conforming to the room were used, whereas for complex vaults, more difficult to be modeled in Revit, the Rhino inside Revit plugin was used, enabling 3D modeling in Rhinoceros and direct export to Revit via Grasshopper (Figure 5).

Lastly, the artworks and furnishings inside the art gallery were modeled by creating parametric families featuring only three parameters: length, width, and height. This practice addresses the reduction in computational effort, thus obtaining reasonable LOG and focusing primarily on the LOI.

Focusing on the Level of Development (LOD) of the HBIM model, two different approaches were adopted: one for the architectural elements of the building and another for the artworks of the collections. For the architectural elements, an LOD E was chosen to achieve an accurate geometric representation, particularly for the external elements. For displayed artworks, a lower level of detail (LOD C) was chosen, representing the objects in a more schematic manner. The use of different levels of detail allowed us to optimize the modeling phase, also considering the possibility of exploiting other solutions to virtually represent the artworks as subsequently described.

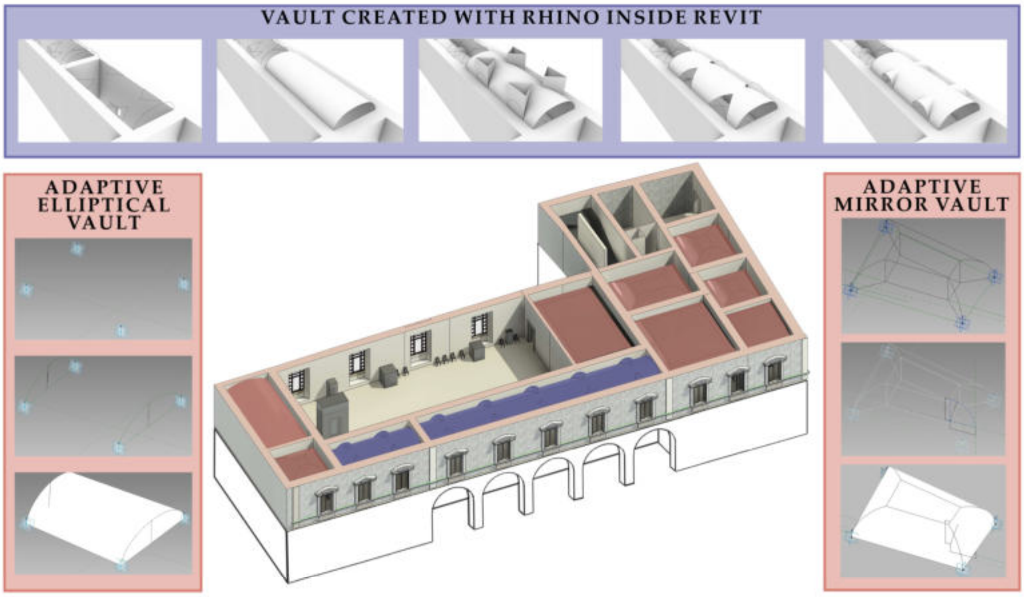


Figure 5. Procedural modeling of the vaults.

According to the model purposes, information was therefore associated with three main layers: building, collections, and facility systems (Figure 1—data enrichment). As in already mentioned research [20,21] for MBIM implementation, a mandatory phase is the generation of a dataset that encompasses data on both the building (container) and the collections housed within it (content), namely the artworks. Various regulatory references were followed for the implementation of data on the displayed artworks, specifically the Ministerial Decree of 1 May 2001, attachment A (article 150, paragraph 6, of Legislative Decree No. 112 of 1998).

For the collection, Revit shared parameters related to artifact features and cataloging standards have been used in order to perform the data enrichment; in particular, data foreseen in the inventory sheets, such as inventory number, object type and dating, name and author, location, material, dimensions, and type of acquisition. Meanwhile, for their conservation sheet, the parameters have included the allowable range of relative humidity, the allowable temperature range, and illuminance values.

Moreover, the data enrichment of the model was intended not only for museum curators but also for technicians and administrations responsible for the management of museum buildings. The model, therefore, includes information about its structure, lighting systems, climate control, security, etc. The sheet associated with surveillance systems (cameras and motion sensors), along with their technical data, includes the identification number, location, and height from the ground of the devices.

Regarding the architectural aspect, we can mention the example of masonry, which includes information about stratigraphy, thickness, typology (exterior/interior), the name of the family, and the class of resistance, which are particularly suitable and interesting for the case study (Figure 6).

The final output is an HBIM model obtained by assembling and combining parametric families with individual objects specifically created for non-repeatable elements and artworks. All instances were organized by leveraging the native Revit data structure, ensuring the consistency of key relationships: for instance, the motion sensor retains its connection with the hosting wall, and the artifacts are linked to the rooms that contain them, thereby facilitating all subsequent management operations. Moreover, the custom shared parameters defined in Revit for artworks and furniture were grouped into custom property sets, ensuring a structured and standardized organization of information (Table 3).

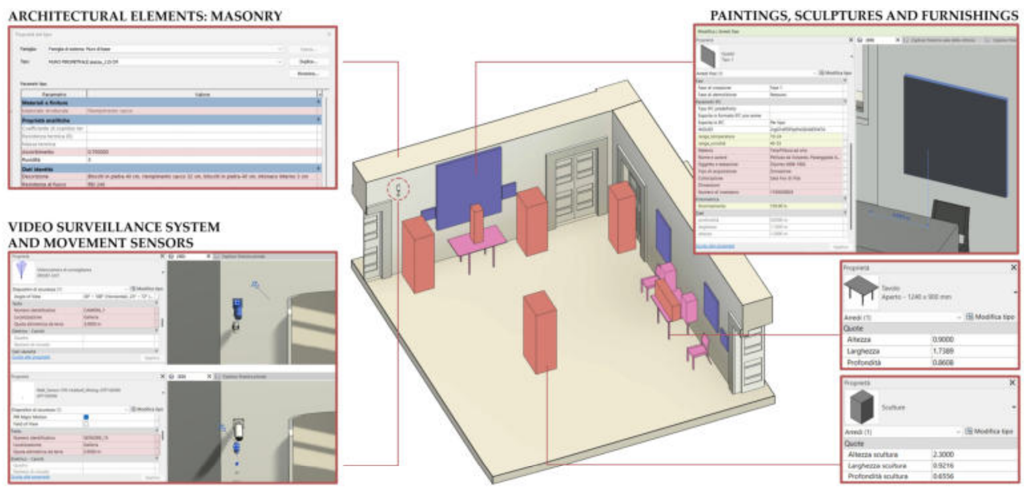


Figure 6. Three-dimensional modeling and data enrichment of architectural elements, artworks, furniture, and security systems. Examples of high LOI (on the left) and low LOG (on the right).

Table 3. Artworks and furniture-related Custom Pset.

Element	Custom Pset
Artwork	Pset_ArtworkIdentification Pset_MountingAndPlacement Pset_ConservationCondition Pset_EnvironmentalRequirements Pset_ProvenanceAndDocumentation
Furniture	Pset_FurnitureIdentification Pset_ConservationCondition Pset_ProvenanceAndDocumentation

2.3. Prototype: The Virtual Advanced Resource Management from BIM for Museums

After obtaining the HBIM model as previously discussed and correctly implementing it with the informational layer, a key step of the methodology consists of setting up a prototype to provide virtual access to the 3D models and related data. Considering the low level of geometric detail, the main aim was to obtain a unique tool in which MBIM data enrichment and visual completeness from spherical panoramas mutually support each other. The prototype has been designed as a desktop application to enable the use of the HBIM model to facilitate its visualization and consultation (Figure 7).

The users can immerse themselves in the HBIM model and freely explore architectural elements such as walls, floors, stairs, and load-bearing structures. Since it does not include material shaders, it is supported for object recognition by labels and different colors.

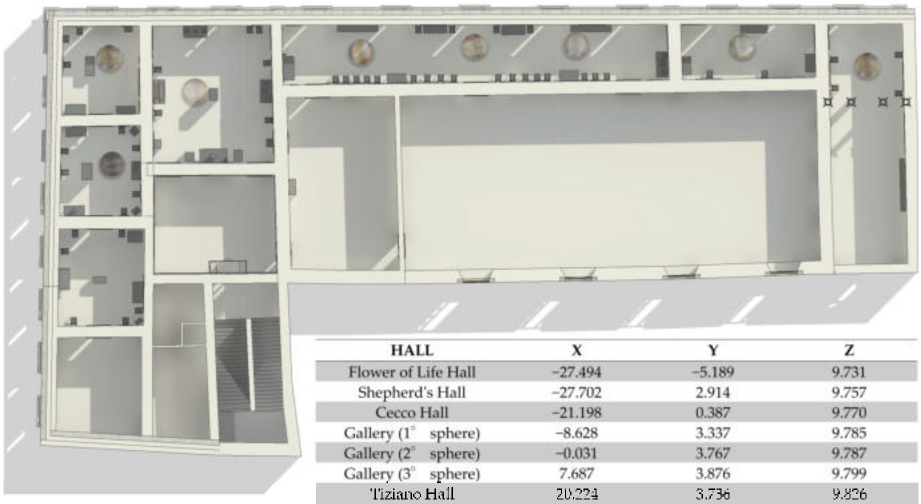
Moreover, the prototype offers the possibility to combine the HBIM model with spherical panoramas, offering both high visual quality and the ability to query elements, resulting in output data extracted from the BIM.

At the operational level, the connection between the BIM environment and the spherical panoramas was established within the Unity game engine 2022.3.24f1 using the correct alignment of the panoramic overviews to the HBIM model. Therefore, spheres were created within the Cyclone 3DR software, exploiting the same file previously used to decimate and segment the point cloud of the building. The center of each sphere was associated with a scan station, and then its surface was textured using the equirectangular images, which had already been aligned to the corresponding scan station to associate RGB values to its points (Figure 8).

Figure 7. Comparison of 3D model view and panoramic view from the same standpoint.

About the interaction system, we chose a hybrid approach for the movement of the camera, linked to the navigation of the 3D environment and spherical panoramas. For the exploration of the 3D model, a system with 6 degrees of freedom was chosen, allowing both translation and rotation of the point of view, using the keyboard commands a-w-d-s for the translations and the mouse movement for the camera rotation. The navigation of the panoramas was characterized by 3 degrees of freedom; the user can move the mouse to rotate the camera, constraining the translation coordinates of the point of view in the predefined acquisition point. The interaction with the elements of interest was performed by right-clicking the mouse on the queried objects to show tables accompanied by BIM information levels.

The need to keep the data entered in the BIM model also within the app was mandatory, also avoiding their further insertion. Since Unity does not natively support the IFC format, it was necessary to use a specific plugin. This allows for the exact information from Revit to be read in Unity's inspector. These data are then retrieved in-game within tables through further implementation of the IFC importer script. Specifically, the developed script redirects the exported data from the Unity inspector to the in-game interface, preserving the data structure defined in Revit through IFC, as previously described. The process is automatic and avoids manual data transcription from one SW environment to another (Figure 9).



HALL	X	Y	Z
Flower of Life Hall	−27.494	−5.189	9.731
Shepherd's Hall	−27.702	2.914	9.757
Cecco Hall	−21.198	0.387	9.770
Gallery (1° sphere)	−8.628	3.337	9.785
Gallery (2° sphere)	−0.031	3.767	9.787
Gallery (3° sphere)	7.687	3.876	9.799
Tiziano Hall	20.224	3.736	9.826
Finale Hall	29.745	2.322	9.822

Figure 8. Plan layout of the arrangement of textured spheres in the exhibition halls. Spatial coordinates (x, y, z) have been assigned to each sphere, corresponding to the acquisition position of the respective equirectangular image.

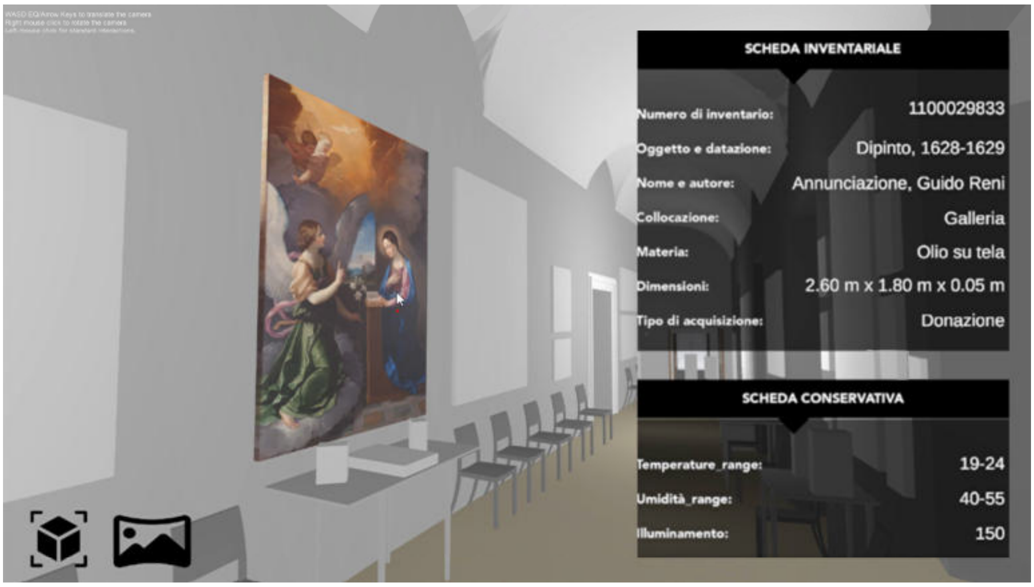


Figure 9. Interaction with a painting and access to its information tables. On the right: at the top, the inventory record; at the bottom, the conservation record.So, this viewing mode connects two usually separate databases, as images implicitly contain richer semantics than represented by simplified models. Indeed, in addition to being a powerful visual support tool, in our prototype the images can gather information about all conservation and management data stored in BIM objects, as well as detailed descriptions of objects present in the rooms of the Pinacoteca and their positions.

3. Results and Discussion

This present work has effectively taken advantage of integration between BIM methodology and XR technologies to broaden the BIM range of applications, offering significant innovative solutions for documentation and dissemination of cultural heritage. The distinguishing characteristic of BIM is its potential in collecting heterogeneous information, even so linked to the 3D geometric representation. The inclusion of information within a 3D model serves as the pivotal factor that allows it to work as a database and a powerful communication tool among professionals from different fields. The main achievement of the developed workflow lies in its ability to seamlessly integrate HBIM and VR into a multilayered platform, presenting an innovative approach to architectural and museum heritage management and preservation. By harnessing the power of HBIM, which facilitates the creation of digital twins and informed models of historical structures, and combining it with immersive VR technology, the platform offers an experience for stakeholders to explore and interact with heritage places in a virtual environment. This integration not only enhances the visualization and understanding of historical buildings but also enables informed decision-making regarding conservation and organization tasks. Moreover, the multilayered nature of the platform allows for the incorporation of heterogeneous data sources, such as historical records, constructive information, conservative data, surveillance data, and cataloging information, enriching the virtual knowledge of the site.

In this presented study, the scan-to-BIM methodology was applied to the first floor of the Civic Art Gallery of Ascoli Piceno. This involved conducting a 3D survey using laser scanning combined with high-resolution spherical panoramic imaging. The first result is an enriched model designed to facilitate the management and exploration of this cultural site. Additionally, it was implemented with data obtained through other digitization methods and the development of a multi-layered VR platform to interact with both the building and its collections models. According to UNI 11337 standards, the representation reached an "LOD E" (defined object) level of detail, while the collections achieved an "LOD C" (simplified object) level. Regarding the latter, information from literature, museum catalogs, and existing regulations has been methodically integrated into the BIM model. Specifically, a thorough cataloging of the masterpieces of the collection has been undertaken, ensuring the inclusion of all relevant and suitable details. Concerning the building, the HBIM model has been enriched with information about both past and upcoming restoration interventions, resulting in a comprehensive historical record. Additionally, details regarding security systems and structural elements have been integrated, stressing the potential of HBIM as a collector of information able to support the management of a museum.

Undoubtedly, the simplified modeling of the building and collections has reduced the time required for implementation, making this process sustainable. To complement this simplified modeling approach, spherical panoramas have been incorporated into the HBIM model, facilitating the development of a robust VR tool for building management. The data contained within the BIM model can be seamlessly displayed within photographic images. Since the data is directly drawn from the model, there is no need for reloading, thus avoiding transcription errors or additional steps of panorama annotation (Figure 10).

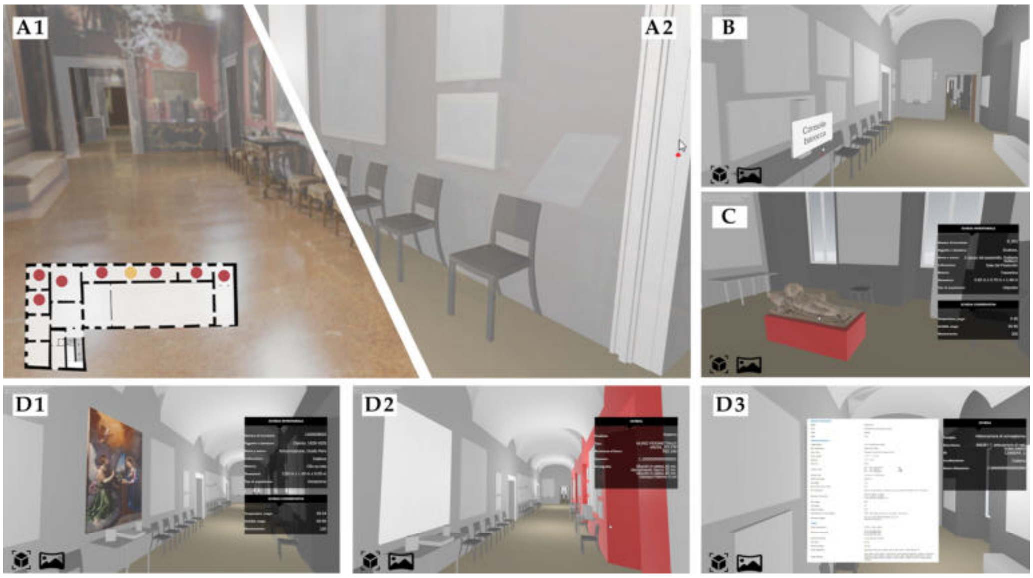


Figure 10. Main features of the prototype: (**A1**,**A2**) overlapping of panoramic view and HBIM, (**B**) HBIM view with low detail, (**C**) visualization of detailed 3D models of the artifact (**D1**–**D3**), and browsing of different data enrichment.

4. Conclusions and Future Works

This paper aims to take a step forward in the integration of MBIM data and immersive environments, thus enabling the management and inspection of the historical building and the collection herein hosted. This interoperability is particularly robust as it is based on an already available TLS/panoramic images survey campaign and on geometrical coordinates from the scan stations. In this sense the article proposes a set of families with low LOD and high LOI to be integrated by 360° views of the art gallery. It is worth mentioning the use of the open-source game engine (Unity) proposed for the visualization of panoramic images and HBIM models with the connected IFC and all the consistent data enrichment, although further research is investigating in depth the possibility of using completely open workflows [36]. This proposal could be considered of great interest in the management of built heritage since it allows us to exploit the visual accuracy of panoramas (which is partially lost when transformed into HBIM), as well as the advantages of informed object modeling. In our study case, the latter is a resource of great relevance since it allows us to check the data enrichment and all the layers of information outside proprietary and authoring SW. Although several interoperable workflows from HBIM to VR are growing harnessed [37], the prototype developed in this research stands out for its focus on the management of built heritage and museum collections, highlighting its innovative approach. Taking future sustainability into account, it can be stated that, with a heterogeneous dataset encompassing point clouds, panoramic images, and digital replicas of artworks, the lack of highly detailed parametric 3D modeling has been overcome by harnessing the distinct advantages of the different digitization techniques. Regarding digital replicas of the artworks, it must be underlined that existing data, for which resources have already been allocated in terms of both finances and time, were leveraged. So, the primary challenge will lie in correctly integrating further data and representations within the presented multi-layered VR platform, that in this way will continue to serve as a support tool for managing the museum and all the professionals engaged in its operation. Thus, further investigations may delve deeper into the analysis of wall stratigraphy and the specific materials employed, offering valuable insights into key aspects such as the energy management of a historic building. Moreover, a future development could focus on the artworks preservation within the museum halls through the implementation of environmental parameter monitoring systems. These systems, when compared to the optimal value ranges for artwork preservation, could establish a continuous monitoring and alerting system in case critical thresholds are exceeded.

Another potential future development of the prototype could involve the integration of data directly within the VR environment, followed by the reintegration of this data back into the HBIM model, establishing a two-way information exchange [38]. The data integration within the multi-layer platform would empower users to directly interact with digital replicas, not only by accessing annotations or additional data already linked to each object but also by enabling them to actively enhance the model with further information. An additional task that can ensure robustness of the workflow is envisaged in conducting user tests with museum professionals and visitors to gather feedback. This step would help to measure the effectiveness and efficiency of the VR application in managing collections and CH spaces. User tests could be carried out to support the integration of the HBIM–VR interaction, also considering iterating on the workflow and VR application based on user feedback and performance metrics. Through direct observation, gathering user feedback, and analyzing quantitative data, it will be possible to gain a deeper understanding of user performance and preferences.

In conclusion, the presented research showed that the BIM approach can effectively support the conservation and experience of architectural heritage. Although the creation of an accurate model of a historic building is a challenging process, it has been demonstrated how it currently represents an effective investment to enhance the efficiency of interventions, thus ensuring both improved preservation quality and reduced financial impact. Outcomes consist of (a) a validated and documented workflow for converting BIM models to VR environments, (b) a prototype VR application tailored for museum collection management and CH space conservation, and (c) user guidelines and best practices for implementing and utilizing VR in museum management.

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Abbreviations

The following abbreviations are used in this manuscript:

AEC	Architecture, Engineering and Construction industry
BIM	Building Information Modeling
CH	Cultural Heritage
CIM	Collection Information Model
HBIM	Heritage Building Information Modeling
LOD	Level of Detail
LOG	Level of Geometry
LOI	Level of Information
MBIM	Museum Building Information Modeling
SW	Software
TLS	Terrestrial Laser Scanning
UAV	Unmanned Aerial Vehicle
VR	Virtual Reality
VT	Virtual Tour
XR	Extended Reality

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