SCIRES it
SCIentific RESearch and Information Technology
Ricerca Scientifica e Tecnologie dell'Informazione
Vol 14, Issue 2 (2024), 1-12
e-ISSN 2239-4303, DOI 10.2423/i22394303v14n2p1

CASPUR-CIBER Publishing, http://www.sciresit.it

A TAILORED WORKFLOW FOR THE VALORIZATION PROJECTS OF INDUSTRIAL HERITAGE THROUGH A BIM-BASED VR EXPERIENCE

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Abstract

Digital information systems became a pivotal opportunity to enhance the heritage investigation, documentation, valorization as well as the dissemination of cultural values embodied in modern heritage assets. Industrial heritage represents a paradigmatic field, often showing accessibility issues, complexity for the users in discerning the site's evolution phases, and the specific production process due to the lack of original machinery. Thus, the paper proposes a customized methodological flow for high-definition 3D digital modeling, which can improve the interaction and personalization of immersive cultural experiences and highlight the tangible and intangible values of existing and lost heritage. The workflow was tested on the Mecenate paper mill in Tivoli, Rome and the aim was to realize a virtual tour, addressing two specific issues in the storytelling of the factory: the lack of the original machinery and the loss of innovative lightweight metal roofing design by Gino Covre.

Keywords

Industrial heritage, H-BIM, virtual reality (VR), digital valorization processes, document-based modeling, Gino Covre

1. *Introduction*

The loss of machines, the partial or total disappearance of building components, buildings and production infrastructure, makes it arduous for researchers and users to understand the history of an industrial site with a long history. The evolution in recent decades of digital tools has come to useful aid especially in those cases where complexity made it no possible to work with traditional representations (Cui et al., 2023). The extension to the communicative and disseminative dimension has thus found new opportunities both for direct fruition, with augmented reality, and for new fruition of inaccessible or lost areas, thanks to virtual experiences.

The "historical" BIM has proven to be a tool of many potentials, but beyond the representation of a built object, its use in research and dissemination has shown the need to extend both interoperability and operate, with greater development of interoperability, between authoring and tools (Garagnani et al., 2021; Bruno & De Fino, 2021). The paper proposes a tailored methodological workflow for high-definition 3D digital modeling of the industrial heritage of the modern movement, able to enhance interaction and customization of immersive cultural experiences and highlight tangible and intangible values in both still existing and lost heritage.

Moreover, the loss of old parts of buildings makes it difficult to read the relation between the built architecture and its industrial nature. Starting from a review of the various approaches introduced in the recent literature, an exemplary case study provides the best illustration of the different potentials: the exceptional system of the Mecenate paper mill in Tivoli (Rome), constructed in the XX century onto the Roman Sanctuary of Hercules Victor.

In fact, the case study, the subject of previous experimental processes of collecting and systematizing its data digitally (Currà, D'Amico, & Angelosanti, 2022; Currà et al., 2023), provides the opportunity to propose a virtual tour, addressing the two specific issues of the lack of the original machinery-necessary for the description of the production process-and the loss of an innovative lightweight metal roofing (designed by Gino Covre), which is essential for revealing the architectural and construction values.

Despite the proposed methodology adopting a time-consuming modeling solution – based on scan-to-BIM procedures – the results of the presented project highlight how a detailed digital "re-construction" of the architectural heritage is pivotal for the valorization and conservation processes of the industrial heritage. Further expected outcomes can support public institutions in defining new forms of fruition, communication, and interventions.

1.1 Digitalization processes and virtual reality for heritage valorization

Current digitalization processes represent an intriguing opportunity to enhance communication and dissemination of cultural values embodied in modern heritage assets.

In recent years, thanks to rapid technological developments, the creation of digital information systems has become a key issue in the debate concerning methods and tools applied to heritage investigation, documentation, and valorization. In this context, in order to involve a broader public of both expert and non-expert users, the researcher has been encouraged to explore novel directions in the heritage representation field, moving beyond the idea of the digital model as a merely geometrical visualization and data repository (Salvador García, García-Valldecabres, & Viñals Blasco, 2018).

Particularly, besides the digital representation procedures based on the definition of reality-based 3D models (Remondino et al., 2018), some advanced approaches in cultural heritage valorization based on interactive and immersive experiences for the general audience have been proposed (Banfi, Stanga, & Landi, 2023). These include Virtual Reality (VR) tools that can ensure an accurate representation of historical structures and offer better accessibility and fruition conditions, with the purposes of public cultural dissemination, (Condorelli, Luigini, & Nicastro, 2024) (Fanani & Syarif, 2023), education activities (Condorelli, Luigini, & Nicastro, 2024) academic research (Izaguirre, Ferrari, & Acuto 2024), condition assessment (De Fino, Bruno, & Fatiguso, 2022; Savini et al., 2022) and risk management (Lee et al., 2019).

In the field of VR-based documentation and communication of historic sites, a specific research area is focused on the concept of "lost" architectural heritage, namely buildings, structures and physical entities of the built environment that have been damaged or altered over time by neglect, disaster, demolition, or renovation works to such an extent that they are irretrievable through onsite experience (Rafeiro & Tomé, 2023). In this case, digital replicas of missing parts are reconstructed based on rigorous historical research, including ancient manuscripts, letters and official reports (Banfi, Stanga, & Landi 2023), photos, videos, miniatures and blueprints (Fanani & Syarif, 2023), as well as artefacts relocated in museum exhibitions (Denker 2023). Moreover, they are integrated in 3D models of the current "as found" state based on Terrestrial Laser Scanner (TLS) survey (Rafeiro & Tomé, 2023), also in combination with digital photogrammetry to get high-resolution 3D textured models and orthophotos (Banfi et al., 2021). Thus, merged virtual environments are created, generally, based on Historic/Heritage Building Information Modelling (HBIM), that has been increasingly acknowledged as a valuable tool for both disseminating the value of historic architecture and managing the public use of heritage assets (Salvador García, García-Valldecabres, & Viñals Blasco, 2018).

The resulting VR solutions might show different levels of immersion and interactivity. They might rely on web consultation with mobile devices of recorded videos (Rafeiro & Tomé, 2023) or scenes where the users utilize viewports to seamlessly teleport and navigate through the informative content (Banfi, Stanga, & Landi, 2023; Gunay 2021). Alternatively, they might enable the immersive fruition by headsets of virtual tours (Merchán, & Pérez, 2020), in some cases enriched by hotspots describing, trough texts and images, some specific areas of cultural interest, along with some background information on the reconstruction approach (Rafeiro, Tomé, & Nazário, 2024). The immersive mode might be further empowered by manipulation of virtual items and interaction with virtual characters, according to a game approach (Kaplan, 2022).

Within the outlined framework, it should be observed that, despite the limited and very recent applications (Prizeman, Davis, & Tam, 2023; Sparrow et al., 2024) (Mezzino, 2023), industrial heritage represents a paradigmatic case study, often showing accessibility issues, complexity for the users in discerning the site's evolution phases, and difficulty in understanding the specific production process due to the lack of original machinery (Currà, D'Amico, & Angelosanti, 2022). Moreover, the lack of machinery or the loss of old parts of buildings makes it difficult to read the relation between the built architecture and its industrial nature. Consequently, further research should be addressed to the virtual fruition of industrial heritage sites by general public and conservation specialists, taking into account that numerous studies have already reached mature results in the digital representation of these assets, including the reconstruction of their missing parts, based on 3D photogrammetry modelling and image rendering (Gutiérrez-Pérez, 2023), as well as by HBIM (Gürcanlı & Hartmann, 2024).

1.2 Industrial heritage and values of the Modern

In the contemporary definition of the city, a pivotal role is assumed by the cultural and heritage resources of the recent past, to which increasingly specific categories of value are attributed. Nonetheless, it is challenging to foresee the balance between the potential of these resources from the twentieth century and the modifications caused by valorization projects. The industrial heritage of the twentieth century is a multifaceted heritage that includes different phases, innovations, revolutions, and unsuspected historical-economic continuities. There are outstanding sites and excellence in series that can only be explored by absorbing, from the realm of Industrial Archaeology, the interdisciplinary approach promoted by national associations, such as CILAC or AIPAI, and international ones, such as TICCIH and ICOMOS (TICCIH & ICOMOS, 2011).

The industrial assets are intrinsically representative of modernity; they can embody various attributes, such as technological evolution, social innovation, economic events, and architectural and urban experiments, as well highlighted primarily by the Nizhny-Tagil Charter of 2003 (TICCIH, 2003).

Recent studies have further emphasized the values embodied in the relationships between machinery and labor generated firstly in the society of the time and nowadays as values transferred to the present. The evaluative investigation thus conducted allows us to identify that its constitutive fragilities "are mainly determined by being the result of incessant, widespread, stubborn, ideative-experimental activity on the machinery, on the buildings, and, fundamentally, on man. It follows that the systems to which reference to plan the correct conservation of this heritage are many. They range from the machinery (tools, engines, transmissions, generators, etc.), to construction (factories, infrastructure, residences, workers' neighborhoods and cities, bourgeois enclaves, etc.), to society (intensity, mode, and duration of work, collective, community or family living, welfare, services, etc." (Currà, 2022, 16-27).

Additionally, the architecture for the industry of the XX century can be considered as an "ideal laboratory" for the experimentation of new materials and technological solutions elaborated to respond to the increased production needs (Giannetti, Russo, & Severi, 2021). Large spans, daylighting, fire protection and resistance, and occupational safety are just some of the performances required at higher levels to the industrial organism and its structures.

2. Methodology

In order to highlight the tangible and intangible values of both still-existing and lost parts of modern industrial heritage, the paper proposes a tailored methodological workflow based on high-definition 3D digital modeling (Fig. 1).

Enhancing the interaction and customization of immersive cultural experiences, the workflow encompasses the following phases: i) integrated survey (photogrammetry and laser scanning) for the acquisition of point clouds, ii) parametric modeling through scan-to-HBIM process of the building, iii) document-based parametric modeling of the lost heritage (machinery and roofing system), iv) BIM-to-VR data processing and VR environment setting up, including visual rendering, user perspective and motion modes, development and implementation of historical and original digital contents.

2.1. Between archeology, modern and industrial heritage: the case study of Mecenate paper mill in Tivoli

The proposed workflow was tested on the exceptional system of the Mecenate paper mill in Tivoli (Rome), constructed in the XX century onto the Roman Sanctuary of Hercules Victor, addressing two specific issues in the storytelling of the factory: the lack of the original machinery – necessary for the description of the production process – and the loss of lightweight metal roofing design by Gino Covre – essential to reveal the architectural and construction values.

The Mecenate paper mill was established in 1887 at the Sanctuary of Hercules Victor in Tivoli. The main reason for choosing this location was to exploit the hydraulic potential of the Aniene River through facilities designed by engineer Raffaele Canevari, which were primarily used for electricity production at that time.

For decades, the paper mill was the most significant industrial complex on the former religious site. Historically, this area had hosted various manufacturing activities, most notably a major ironworks that had been in continuous operation under multiple owners since the Napoleonic era.

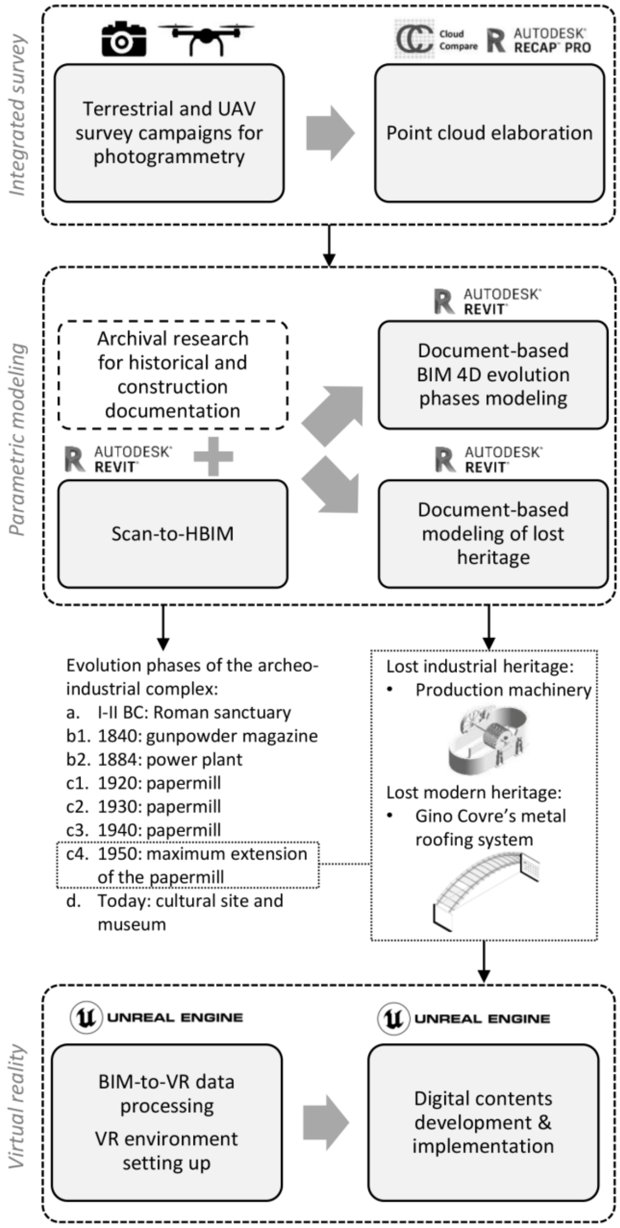

Fig. 1: The methodological workflow proposed: from integrated survey to parametric modeling and virtual tour setting. © Authors, 2024.

The most remarkable transformation occurred between the 1930s and 1950s with the construction of reinforced concrete structures on the ancient Roman remains, all under the direction of engineer Emo Salvati. In 1938, alongside owner Marco Segrè, Salvati commissioned Gino Covre to design lightweight metal roofing. Covre, who had a long-standing association with the Antonio Badoni company in Lecco and had relocated to Rome in 1935, had secured several patents during that period, including one in 1936 for a "vaulted arch made from framed elements".

Indeed, the experimentation of integrated digital fruition within the museum complex would enhance visitors' engagement and allow a deeper exploration and appreciation of the site's multiple cultural and material structures.

3. *Results*

3.1. From integrated survey to high-definition parametric modeling

3.1.1 Scan-to-BIM process of the Roman Sanctuary of Hercules Victor

The survey of the Roman Sanctuary of Hercules Victor had to handle the accessibility issues of some external or non-secure parts of the structures. To obtain a complete dense point cloud of the complex site, the survey procedure has been accomplished by integrating different digital photogrammetry techniques (Remondino, 2011): a close-range terrestrial image acquisition – using a Sony A7R camera – and two low-altitude Unmanned Aerial Vehicle (UAV) flights – using a DJI Phantom 4 drone.

The close-range terrestrial photographic acquisition campaign was conducted on all accessible internal and external spaces of the paper mill. The two flight campaigns have been planned with different aims and applying specific techniques. The first flight was performed in manual mode with a GPS stabilizer in order to obtain images of the external part of the structures, the roofing systems, and part of the surrounding landscape (Fig. 2A). The second flight exploited videogrammetry processes (Torresani & Remondino, 2019) to explore the inaccessible and dangerous internal parts of the paper mill; in this case, the flight was operated without a GPS stabilizer, acquiring more images to ensure a correct overlapping among them and obtain a higher definition of the point cloud.

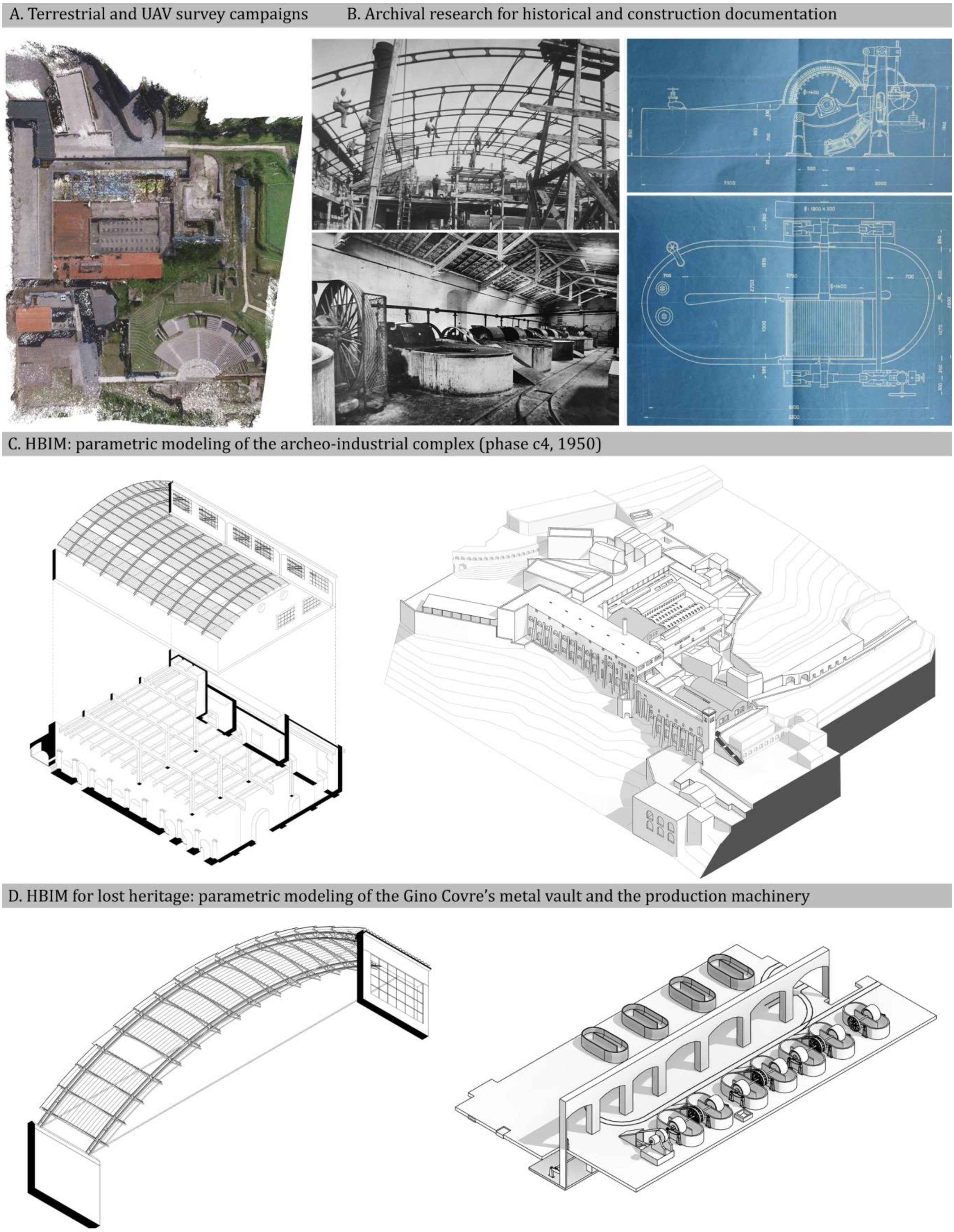

Fig. 2: Steps towards the parametric modeling of the archeo-industrial complex of the Mecenate papermill in the Roman Sanctuary of Hercules Victor (Tivoli, Rome). © A. Marco Angelosanti, 2021; B. Salvati/Perini Archive, Archivio Centrale dello Stato; C. Andrea De Pace, Riccardo Rocchi, 2022 (Currà, D'Amico, & Angelosanti, 2022; Currà et al. 2023); Cassia De Lian Cui, D. Andrea De Pace, Riccardo Rocchi, 2024.

For the integrated survey, 1961 images were acquired and processed with Agisoft Metashape® version 1.5.1. The obtained point cloud has been firstly decimated and cleaned using CloudCompare version 2.11.3, converted from .e57 to .rcs in Autodesk Recap®, and then imported into Autodesk Revit® as a base for the next H-BIM modeling phase.

3.1.2 Document-based modeling of the lost heritage: Mecenate paper mill machinery and Gino Covre's metal vault

In line with the ArchaeoBIM principles (Garagnani et al., 2021), eight evolutionary phases of the archeo-industrial complex have been modeled by exploiting Revit's project phases manager and combining information from the survey with historical documents (Fig. 2B). The 4D diachronic H-BIM model obtained encompasses phases representing the different uses of the complex over the centuries: a. The Roman phase as a sanctuary (II-I BC), b. Two nineteenth-century phases as gunpowder magazine with the Canevari canal and power plant construction (1840 and 1884), c. four phases as a paper mill (1920, 1930, 1940, 1950) (Fig. 2C), d. the current phase as archeological site and museum.

The model has been accomplished using an object-oriented approach, taking into account the peculiarities of Roman, industrial, and modern construction features and building components. Geometric and informational data were represented in specific family instances, overcoming the limit of BIM authoring software towards the standardization of the building components.

Moreover, a tailored procedure has been arranged to model the lost industrial machinery and Gino Covre's metal vault – demolished in 1990 –, integrated in the phase of 1950, the last and more extended stage as paper mill (Currà et al., 2023) (Fig. 2C).

Elaborating a proposal to adjust the Level Of Details concept (LOD, according to UNI 11.300) also to non-industrialized elements, it was possible to represent the shredder Hollander beaters and Gino Covre's metal using a LOD F, basing the reconstruction on historical documents and technical archival records (Fig. 2D). The LOD F chosen corresponds to the more geometrically detailed version of the objects, in which are also integrated information about the construction, installation, manufacturer, and designer, suitable for the valorization aims of the VR tour.

3.2 VR tour

3.2.1 BIM-to-VR data processing and VR environment setting up

The VR environment has been developed based on the H-BIM model of the archeo-industrial complex, purposely integrated with the lost industrial machinery and Gino Covre's metal vault. To this end, the preliminary BIM-To-VR phase has relied on a process of geometric and informational re-encoding, in order to preserve the formal representation of the building and components included in the model, ensure the same LOG (Level of Geometry) from the BIM authoring phase, and maintain the hierarchical and ontological characterization, in terms of class, entity, relationships, shape, and position. Consequently, each asset has kept the corresponding set of attributes (e.g., GUID-Globally Unique IDentifier, Property set, QTO-Quantity Take-Off) in view of integrating the information flows into the simulated environment (Fig. 3A). Similarly, in the virtual design process, building elements were textured preserving material-object relationships, as defined in the IFC file, based on material instances. This approach allowed to preserve the association of elements to the IfcMaterial and IfcMaterialLayer IFC classes, defined in BIM authoring phase.

For the implementation of the Virtual Tour, the model has been imported into Epic Unreal Engine 5 ® simulative programming environment for the surface texturing and light mapping of the scene and the following development of the user interface and implementation of informative cultural contents. Particularly, it has been decided to display solid surfaces with neutral colors of the structural elements – concrete, steel, and wood – along with natural lighting only, to better emphasize the spatial qualities, volumes, and dimensional relationships among rooms, building elements, and the objects contained within them. Particularly, for the scene lighting, the Global Illumination has been exploited with post-processing volumes capable of simulating "light scattering" effects, so as to achieve a more engaging atmosphere (Fig. 3B). In more detail, rendering of Global Illumination and Reflections was handled using the software's internal RT

Fig. 3: Illustrative screenshots of the VR environment and tour; QR code for a demonstration video of the VR tour. © Authors, 2024.

Fig. 4: Visual dashboard for audit Lumen performance. From top left clockwise: Geometry Normal, Reflection Raytracing, Surface Cache coverage, Lumen scene visualization. © Riccardo Tavolare, 2024.

LUMEN engine (Tan, 2024), while the external Skylight was mapped using HDRI images on cubic projection (Fig. 4). This choice produced better color and light perception by using images with wide illumination range. Concerning the perspective, the user interacts with the virtual world from a first-person view, thus seeing the scenes through the virtual character's eyes. The choice has meant to empower a sense of embodiment toward the virtual body through self-location and ownership instead of a third-person view, when the user plays as an avatar with a camera view behind the virtual body.

Furthermore, free locomotion has been preferred to teleporting from one pre-set wait point to another in order to mimic a physical visit and make the visitor able to explore the scenes. To this end, the simulation is based on movement with 6 DoF (Degree of Freedom) through a free environment.

3.2.2 Digital contents and interaction

As far as the informative historical contents are concerned, some of them are generally referred to the rooms, namely the Hollander beaters room, where the paper pulp was prepared for the third machine; the paper storage room, including the sacred area of the Triporticus north of the podium of the temple, and the paper selection room, featured by the above-mentioned very light metal barrel vault and wavy panels for the roof. Further contents specifically referred to targeted objects in the above-mentioned rooms, such as the Hollander machine, used in papermaking to break down raw materials such as plant fibers into pulp suitable for making paper; the façade of the Roman Triporticus, with masonry reticulated face, originally plastered and decorated; and Gino Covre's metal vault. In all cases, the contents are delivered by exhibition panels (Fig. 3C-D), with one historic picture from the Archives of Salvati/Perini and a short textual description that could also be accompanied by off-screen narration to enhance immersion in the virtual scene. The panel solution has appeared interesting, especially considering potential future developments for Augmented Reality utilization directly on-site. The position of the panels is indicated by hotspots: the interaction programming with hotspots is based on responsive areas – triggers – able to detect the presence of the user and activate the related information panels or lifting platform, connecting ground and first levels (Fig. 3E). This mode facilitates human-machine interaction, allowing a faster learning and interaction approach, which is paramount for these types of VR products.

A demonstration of the overall Virtual Tour is available on the webpage, accessible through the QR code (Fig. 3).

4. Conclusion

Starting from the theoretical base of industrial archeology methods and archeoBIM principles, the paper presented a tailored methodological workflow based on high-definition 3D parametric modeling to support the setting of a virtual reality experience for cultural heritage valorization.

The proposed workflow was applied to the archeo-industrial complex of the Mecenate paper mill in Tivoli (Rome), constructed in the XX century onto the Roman Sanctuary of Hercules Victor.

The parametric model was realized through a scan-to-BIM procedure, starting from two terrestrial and UAV photogrammetry survey campaigns. Among the eight extension phases modeled using Autodesk Revit ®, the 1950 phase of the Mecenate paper mill was chosen for the aims of this paper, since still presents the metal vault design by Gino Covre as the roofing system of the paper selection room and the original production machinery.

In this context, the virtual environment has been designed to recreate the experience of the sites in their lost complexity of construction experimentations and productive activities, enabling a remote visit enriched with informational content and digital products that support the understanding of the historical stratifications. This experience paves the way for a series of future investigations, which may focus on extending the sensory perception of the scenes, e.g. with the addition of sounds related to the operation of machinery and vibrations conveyed through haptic control devices that would enhance the sense of emplacement and immersion of the users without increasing the computational load from high-realistic settings. Moreover, from the perspective of model virtualization, significant research developments may arise from the possibility of dynamically linking VR representation to BIM 4D authoring models, interactively programming the visual evolution of each component according to time steps and enabling interaction with time-associated information content.

5. Credits

M. Russo: Methodology, Writing - Original Draft, Writing - Review & Editing, Visualization; M. De Fino: Methodology, Writing - Original Draft, Writing - Review & Editing, Supervision; C.D.L. Cui: Software (BIM), Investigation, Writing - Review & Editing, Visualization; R. Tavolare: Software (VR), Writing - Review & Editing, Visualization; F. Fatiguso: Conceptualization, Supervision; E. Currà: Conceptualization, Methodology, Investigation, Writing - Original Draft, Writing - Review & Editing, Supervision, Project administration, Funding acquisition.

6. Acknowledgments

Funding Call for Sapienza Research 2022: Project: "Lost in Translation: Translating into Knowledge Archaeological-Industrial Investigations on Tangible and Intangible Heritage. The Palimpsests of Water Industries in Lazio" (in collaboration with the VaVe Institute, AIPAI, Politecnico di Bari, and the University of Bologna Alma Mater)

Funding Call PRIN MUR 2022: Project “RE^{3}WORK – REsilient REtrofitting and REuse of Water Heritage and Built Environments: Multi-Objective Optimization for Risk Mitigation and Cultural Enhancement” (Grant Number: 2022NSAXYP).

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