Virtual Archaeology Review, **16**(32): 85-99, 2025
https://doi.org10.4995/var.2024.21662

Received: May 1, 2024
Accepted: July 7, 2024

GEOMATICS AND METAVERSE FOR LOST HERITAGE SITES DOCUMENTATION AND DISSEMINATION: THE CASE STUDY OF PALMYRA ROMAN THEATRE (SYRIA)

GEOMÁTICA Y METAVERSO AL SERVICIO DE LA DOCUMENTACIÓN Y DIFUSIÓN DE SITIOS PATRIMONIALES PERDIDOS: EL CASO DEL TEATRO ROMANO DE PALMIRA (SIRIA)

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Highlights:

- Geomatics three-dimensional (3D) reconstruction of lost Syrian heritage (Palmyra Roman Theatre) with spherical photogrammetry, recreating the monument's conditions before its destruction.
- Operations of polygon decimation to optimise the geometry of the 3D model for virtual reality (VR) and metaverse applications, including texturing operations to enhance realism.
- Development of a virtual environment to be explored in a shared and immersive metaverse platform, available online to disseminate the historical significance of the Roman Theatre in Palmyra.

Abstract:

Cultural heritage encompasses both tangible and intangible aspects for each of us, and efforts must be made to safeguard this legacy for future generations. Unfortunately, in addition to natural and environmental degradation, human activities pose a significant threat to the integrity of historical sites. Monuments and architecture have frequently been intentionally destroyed in conflict zones all over the world. Three-dimensional (3D) and virtual technologies can serve as tools to digitally preserve these sites and raise awareness about the importance of historical properties to the general public, particularly when physical sites are at risk or no longer exist. This challenging field of lost heritage is the framework of this project, in which a procedure of geomatics-based techniques such as spherical photogrammetry, 3D modelling and virtual reality (VR) technologies was developed to reconstruct lost historical architecture. The Roman Theatre in Palmyra, Syria, partially destroyed during Syria's war in 2017, serves as a case study. The methodology report starts with the description of the metrological foundation of the 3D model construction, i.e. spherical photogrammetry as developed by Prof. Fangi (Marche Polytechnic University). Then, the geometry optimisation phase carried out to accomplish the VR limitations in terms of polygon count is presented. Ultimately, the procedure for the virtual environment construction is explained, as well as the development of a metaverse scenario to be visited and shared on an online-based platform. This collective virtual experience aims to revive the destroyed architecture and communicate its significance to the public through a collective and interactive virtual exploration. This study also includes experiments to assess user response, providing insights into methodology effectiveness in conveying Palmyra's Theatre historical relevance and shedding light on the users' perceptions of virtual tools usage for lost heritage dissemination. The evaluation questionnaire's results will guide the project's future developments.

Keywords: geomatics; metaverse; spherical photogrammetry; 3D reconstruction; virtual reality (VR); lost heritage

Resumen:

El patrimonio cultural incluye aspectos tangibles e intangibles y es esencial proteger este legado a futuras generaciones. Sin embargo, además de la degradación medioambiental, las actividades humanas representan una amenaza en los sitios históricos. Con frecuencia, los monumentos y la arquitectura son destruidos en zonas de conflicto. Las tecnologías 3D y virtuales pueden ser herramientas valiosas que preserven digitalmente estos lugares y sensibilicen al público sobre su importancia, especialmente cuando los sitios físicos están en peligro o ya no existen. Este campo del patrimonio perdido

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es el enfoque del proyecto, en que se ha desarrollado un procedimiento de técnicas geomáticas, como es la fotogrametría esférica, el modelado 3D y la realidad virtual (RV) que reconstruye la arquitectura histórica perdida. El Teatro romano de Palmira (Siria), parcialmente destruido durante la guerra siria de 2017, representa el caso de estudio. El informe metodológico comienza describiendo la base metrológica del modelo 3D, a partir de la fotogrametría esférica desarrollada por el profesor Fangi (Universidad Politécnica de Marche). Luego, se detalla la fase de optimización de la geometría que cumple con las limitaciones de la RV en términos de polígonos. Finalmente, se explica el procedimiento de construcción del escenario virtual y el desarrollo de una experiencia de metaverso que se podrá visitar y compartir en una plataforma online. Esta experiencia colectiva busca revivir la arquitectura destruida y comunicar su significado al público a través de una exploración virtual interactiva. El estudio incluye experimentos que evalúan la respuesta de los usuarios, proporcionando información sobre la eficacia de la metodología para transmitir la relevancia histórica del Teatro de Palmira y las percepciones sobre el uso de herramientas virtuales en la difusión del patrimonio perdido. Los resultados del cuestionario guiarán la evolución futura del proyecto, mejorando su capacidad para sensibilizar y educar al público sobre la importancia de nuestro patrimonio cultural.

Palabras clave: geomática; metaverso; fotogrametría esférica; reconstrucción 3D; realidad virtual (RV); patrimonio perdido

1. Introduction

What if one day, waking up in Rome, the Colosseum was no longer there, or not as expected? In this century, driven by both conflict and the relentless forces of nature, our world has witnessed a disturbing pattern of heritage destruction. In troubled regions such as Afghanistan, Iraq, Palestine, Syria, Ukraine, and many other places around the world, there has recently been a growing and worrying trend of harm to movable and immovable cultural heritage (CH) during conflicts. Its destruction has in several cases been more than just collateral damage (as seen in the United Nations Security Council Resolution no. 2347 in 2017). We must recognise that their destruction is more than mere collateral damage. At the same time, the fragility of our CH, vulnerable to uncontrollable natural forces, has been underscored by the spectre of natural disasters, including catastrophic earthquakes (Galeazzi et al., 2023; Meghraoui & Sbeinati, 2023).

Nonetheless, numerous historical sites worldwide are threatened by natural hazards or anthropic causes (Al-Barzngy & Khayat, 2023), and several have already faced decline or destruction due to conflicts (De Pascale, 2024). For these endangered or already destroyed sites, and to ensure that future generations can inherit the historical memory of the past, digital and virtual technologies can play a crucial role. The 3D reconstruction of ancient sites through geomatics techniques can serve as a tool to address the threat of losing these vestiges of our past forever (Fangi et al., 2012; Fangi et al., 2017; Bitelli et al., 2017).

The advent of Virtual Reality (VR) technologies has opened up new horizons in the field of CH preservation and dissemination (Bekele et al., 2018; Günay, 2022; Di Stefano et al., 2022). The possibilities offered by virtuality become even more interesting when used in contexts where traditional preservation approaches are not feasible. Indeed, the creation of a virtual environment in which digital objects reconstruct existing (or existed) properties leads to numerous further developments in the fields of documentation, dissemination, education and more (Brůha et al., 2020).

The possibilities increase when considering VR from the perspective of collective interaction, a possibility offered by the metaverse (Huggett, 2020). This technology stands as a virtual counterpart to the real world, enabling people to connect and share places and experiences accessible through (also) VR devices (Mystakidis, 2022). For this research, efforts were made to address all these issues. In this paper, historical and architectural information about Palmyra Roman Theatre, the selected case study for this research, will first be presented. Following this, an overview of the current state of the art in geomatics and VR applied to lost heritage will be provided. In the methodology section, the workflow adopted will be described in detail. Finally, the research outcomes will be discussed, concluding with final considerations and the future perspectives arising from this research.

1.1. The Case Study: historical background and the Roman Theatre and its destruction during the Syrian war

The current territory of the Republic of Syria partially overlaps with the historical region of Syria in the Fertile Crescent. Evidence of various populations is attested by the presence of ruins of Phoenician temples, Greek and Roman theatres, and ancient towns. Later, Islamic populations constructed mosques and citadels, as well as minarets and *madrasah*[1]. Finally, during the Ottoman period, *sougs*[2] and *khans*[3] were built, facilitating trade.

During the last decade, fighting on various fronts has reshaped Syria into different control areas. The conflicts in the region have been a tragedy for the civilian population and have also constituted a threat to Syrian CH. During the war, several heritage sites and properties have been raided and/or destroyed (Shadi & Bashar, 2015). Among them is the site chosen for this project, namely the Roman Theatre in Palmyra, the remains of which lie in the heart of the ancient Acropolis (Fig. 1). The Roman Theatre was constructed starting in the 2^{nd} century along the colonnade facing the city southern gate. The *aditus maximi* of the theatre are 3.5 m wide, leading to a stone-paved orchestra with a diameter of 23.5 m. The orchestra is surrounded by a circular wall of 20.3 m in diameter (Sear, 2007). Largely buried under the sand until the 1950s, the structure has been excavated and restored, representing one of the best-preserved Roman theatres in Syria.

[1] *Madrasah*: Islamic school.
[2] *Souq*: Arab marketplace.
[3] *Khan*: Historical inn for travellers.

Figure 1: Spherical panorama of the Roman Theatre. Credits: Prof. Gabriele Fangi's collection.

Two of the main elements lost during the Syrian war were the pediment of the central portico and the group of central columns. Additionally, the backdrop of the stage, which was adorned with niches for statues and other decorative elements, was also damaged during the 2017 conflict (Bardon, 2017). The original appearance of the building, along with other Syrian monuments, is thus lost forever, but it is preserved in numerous photographic documents, particularly in the thousands of photos acquired by the Italian Professor Gabriele Fangi (Polytechnic University of Marche) during his 2010 (pre-war) trip (Fig. 1). This collection is invaluable because it represents one of the rarest systematic documentations of this heritage. Geomatics scholars still rely on it today to reconstruct the historical sites of the areas he had the chance to visit.

1.2. Metaverse applications for CH virtual reconstruction and dissemination

One of the most important ways to address and mitigate the eventual loss of architectural heritage is by using digital tools. History has been revitalised in recent years due to the rapid advancement of technology, including digitisation using geomatics techniques to VR and augmented reality (AR) systems to explore 3D environments. Even though physical preservation and restoration remain the best strategy to preserve cultural property, digital and virtual tools offer immersive and interactive experiences that allow visitors to discover old buildings and engage with artefacts and historical sites in fresh ways.

In recent years, the concept of the metaverse has started to emerge in the context of virtual worlds. It is a 3D and interactive digital environment that either simulates reality or creates imaginary worlds (Dwivedi et al. 2022), where users can interact with one another and with virtual objects. The metaverse proves to be invaluable in enhancing cultural assets and offering immersive and engaging experiences to visitors (Yang, 2023). This allows them to explore museums, monuments, archaeological sites, and works of art from various perspectives and in different contexts (Longo & Faraci, 2023).

The use of the metaverse concept for heritage applications has been explored in the work of Zhang et al. (2022), aimed at establishing a systematic approach for constructing a CH metaverse to enhance the management and preservation of these assets. A framework is proposed for this CH metaverse, focusing on fundamental elements and mapping between the physical and virtual worlds. Five dimensions of the CH metaverse have been analysed: 1) linearity, 2) planarity, 3) space, 4) time, and 5) context, to provide a better understanding of this concept.

The integration of the metaverse with CH often incorporates the use of 3D modelling. This technique can be applied to historical properties for diverse purposes, including documentation, preservation, restoration, communication, and education (Moneta et al., 2020). 3D modelling enables the development of accurate digital reproductions of historical structures and ancient artefacts. These digital representations can be stored within the metaverse, ensuring their preservation over time and broadening accessibility to a global audience.

In this context, digital twins are used in the work of Cruz et al. (2022), where the aim is to generate and validate a workflow that enables the use of virtual twins derived from unique buildings in our architectural heritage. These virtual twins will ensure the preservation and dissemination of CH while advancing universal accessibility through innovative technologies, including databases, metaverses, VR, AR, or gamification. In establishing this workflow, they used digital twins acquired through photogrammetry.

Various databases and metaverses underwent thorough analysis and selection, aiming to integrate the most fitting ones into an efficient workflow that aligns with specific criteria, such as suitability for deployment in VR and AR environments. A digital strategy based on the application of Non-Fungible Tokens (NFT) for digital twins to preserve and maintain Miao silver technology in the metaverse era is also presented by Wang et al. (2023). These digital replicas represent the artistry of Miao silver, collaboratively produced by Miao silversmiths and 3D technologists. The aim is to contribute to the preservation and advancement of Miao silver heritage, proposing innovative solutions to foster the prosperity of intangible CH on a global scale.

Another work that incorporates the metaverse with CH investigating how the metaverse can be used to preserve traditional culture and historical heritage is presented by Fan et al. (2022). The authors propose a digital documentation framework based on the metaverse, specifically designed for historical figures to meet the requirements of presentations within this virtual environment. The objective is to convert multimodal data associated with CH into digital format and deliver a non-contact virtual experience for research and cultural preservation purposes. Furthermore, the intention is to create an immersive information service for tourists exploring historical sites, exemplified by the Zhu Xi metaverse system. This marks a progressive stride in establishing a metaverse exclusively dedicated to historical figures.

The use of the metaverse for lost heritage can go beyond mere preservation (Pellegrino et al., 2023), offering opportunities for learning and understanding history. It enables present and future generations to experience and appreciate what has been lost over time. Within the metaverse, experts can collaborate to accurately recreate places, works of art or other cultural elements that have been damaged or destroyed over time. In a similar context, Gaffar (2021) explored reconstructing inaccessible and deteriorating heritage. This research employed photogrammetry and videogrammetry techniques, along with photomodelling software, to restore missing sections of historical buildings. This involved image processing and 3D modelling using tools like Trimble SketchUp or Autodesk 3ds Max and with models exported to the Unity game engine for creating fully interactive VR models.

The methodology was applied to generate comprehensive virtual reproductions of inaccessible sites such as the Al-Aqsa Al-Sharif Mosque complex and the deteriorated Badr El-Din El-Waney Mosque. The proportions of the monuments, mosques, gates, and domes were carefully derived from various sources and references, ensuring precise reconstruction. In more recent research (Chehab & Nakhal, 2023), the authors discuss the importance of preserving the buildings and historical structures of a city, as they represent its aesthetic and cultural history, contributing to a sense of belonging and connection with the past. Historical buildings are often demolished and replaced, leaving behind both told and untold stories. To revive the memory of these disappearing buildings, the metaverse and VR tours can play a crucial role. The article focuses on a specific case study concerning the "The Egg" or "Beirut City Centre" building in the city centre, which was unfortunately destroyed and demolished due to unforeseen events.

1.3. Motivation and operational objectives

The focus of this research is on lost CH. Around the world, numerous sites are at risk or have already been destroyed by natural or anthropic disasters. The international community and non-governmental organisations are taking steps to address this critical situation, through awareness-raising campaigns or direct intervention in disaster zones. As part of the scientific community, it is crucial that we leverage our resources and knowledge to help preserve endangered architecture and monuments, many of which are lost forever. To this end, this work aims to demonstrate that digital and virtual technologies can efficiently contribute to the mission of safeguarding vanished cultural properties. To achieve this goal, an integrated methodology of geomatics and VR techniques was tested on the Palmyra Roman Theatre, a prominent example of lost heritage as mentioned in Section 1.1. This Theatre had previously been digitally reconstructed by other scholars. Denker (2017) proposed a 3D reconstruction approach using historical images, documents, and topographic data. In contrast, the work presented in this paper focuses on reconstructing the theatre by means of a geomatics approach, specifically employing spherical photogrammetry. Silver et al. (2018) and Fangi et al. (2022) presented other examples of 3D techniques for reconstructing the monument, demonstrating how digital tools can document and showcase lost heritage.

However, unlike these works, the approach presented here incorporates the use of a metaverse, which was not considered in the aforementioned studies. From an operational point of view, the first task was to optimise a digital model of the Roman Theatre of Palmyra, originally obtained through spherical photogrammetry by the team of Professor Gabriele Fangi several years ago. This involved significantly simplifying the 3D model, which was created using the extensive collection of spherical images acquired by Prof. Fangi during his travels in Syria, to make it suitable for VR platforms (which impose limits in terms of model density). Next, the textures were enhanced to improve the realism of the virtual experience within the metaverse platform. Finally, the immersive platform was tested to assess its capabilities and potential, followed by the administration of a feedback questionnaire to the public to evaluate engagement with the virtual scenario. Detailed descriptions of each stage, from modelling and VR development to user feedback evaluation, will be provided in subsequent sections.

2. Methodology

In this section, the methodology employed to accomplish the project's objectives will be described in detail, outlining each step of the integrated workflow as synthetically described in Figure 2. The choice of software platforms predominantly favours those in open source or free environments, to ensure the replicability of the methodology, but also based on information present in the related literature.

Blender is a well-known platform for 3D modelling, and offers a variety of tools for mesh optimisation, as explained in Section 2.2. Unity, instead, is one of the most used and versatile free game engines. The metaverse platform was selected for its user-friendly interface and direct integration with Unity through the Standard Development Kit (SDK). These issues will be addressed in detail in the next sections.

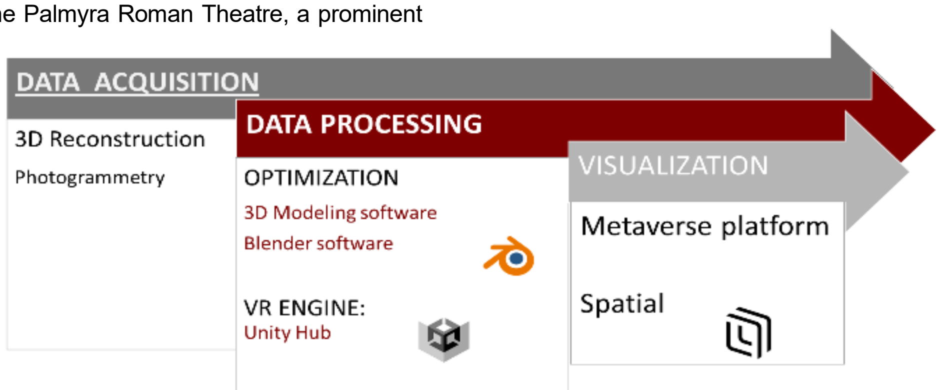


Figure 2: Methodology workflow.

2.1. 3D reconstruction of the Roman Theatre with spherical photogrammetry

The methodology used to create the 3D model for this research is known as spherical photogrammetry (SP), representing the metrological foundation of the reconstruction. This method, perfectioned and tested in several projects by Prof. Fangi (2015), involves the orientation through bundle block adjustment of multiple panoramas and manual reconstruction of 3D objects. Its advantages include the wide field of view (FoV) of the images (up to 360°), reduced costs of instrumentation, and high speed of photo acquisition.The accuracy of the models produced using this technique is comparable to that obtainable with traditional monoscopic photogrammetric methods (Fangi, 2007). SP has been conceived and designed primarily for rapid metric documentation of architectural heritage. 3D models can be created using the aforementioned technique to digitise endangered (or destroyed, if images related to the monument in its entirety are available) structures such as those destroyed by the war in Syria (Doppelhofer, 2019).

In 2010, Prof. Fangi employed this technique to meticulously document 30 Syrian heritage sites, including the renowned Minaret of Aleppo and the Minaret of the Umayyad Mosque, just before the outbreak of war. His ultra-high-definition photographs enabled the virtual reconstruction of these priceless monuments with remarkable fidelity (Fangi, 2019).

The 3D representation of the Roman Theatre of Palmyra, depicted in Figure 3, was created by Professor Fangi's team using various methodologies, including SP and other photogrammetric technologies. This process specifically begins with the exploitation of the coplanarity condition between dual panoramas, utilising a minimum of five tie points. Subsequently, absolute orientation is achieved through a 3D roto-translation process, and bundle block adjustment is executed with at least three stationary points to ensure collinearity.

The reconstruction of the artefact begins with the intersection of corresponding projective rays emanating from oriented panoramas. Intrinsic orientation parameters are predetermined, and image distortion is corrected using stitching software, which merges multiple discrete images into panoramic representations. The dimensional calibration of the model is facilitated through distance measurement acquired on-site or found in archaeological/architectural records, establishing a referential framework for absolute orientation (D'Annibale et al., 2013).

Starting from the orientation of spherical imagery, 3D models can be created based on the principles of projective geometry, employing an image-based interactive modelling approach. This technique is particularly effective for architectural surveys, leveraging the inherent constraints of architectural geometry to streamline the 3D modelling process. The foundational concept of this method revolves around the application of texture-mapping techniques within modelling software, functioning as a virtual image projector of the architectural entity.

By fixing the projection centre and orientation within a 3D virtual space, objects can be generated, manipulated, and modified to align with the projections. Consequently, the objects acquire accurate form and placement within the virtual domain of the detected elements. This constitutes an interactive modelling technique, as the interaction between the modelled objects and the projected images is discernible in real time. To conduct the survey of Theatre, 9 panoramas were used. It was possible to identify homologous points and related polygons created in at least two panoramas. The data processing was conducted to enable the restitution of points and polygons directly in a 3D space, supported by "CAD" software. Figure 3 illustrates the orientation and wireframe of the 3D model, including the bundle rays from each station.

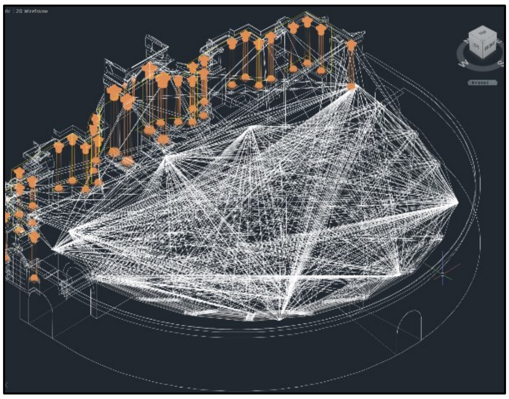


Figure 3: Wireframe of the orientation file, with the 9 acquisition stations and the bundle rays used for the orientation (Ministri, 2015).

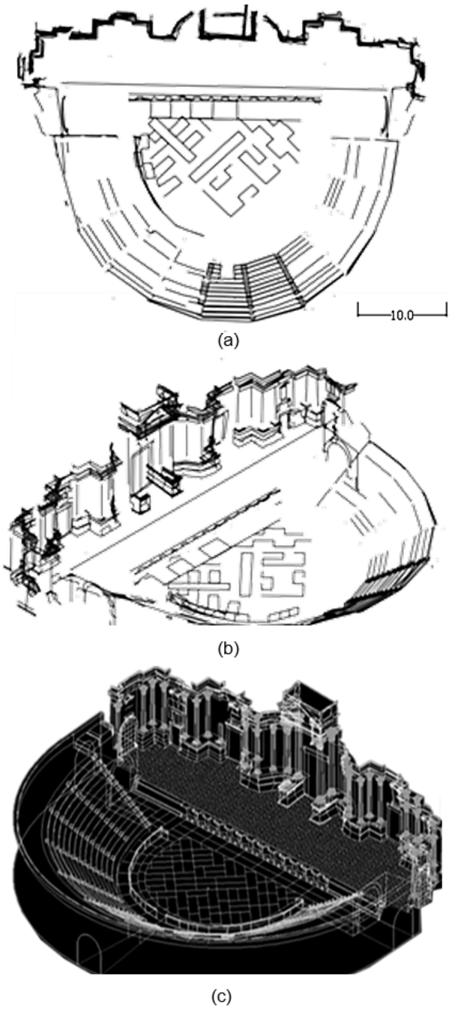
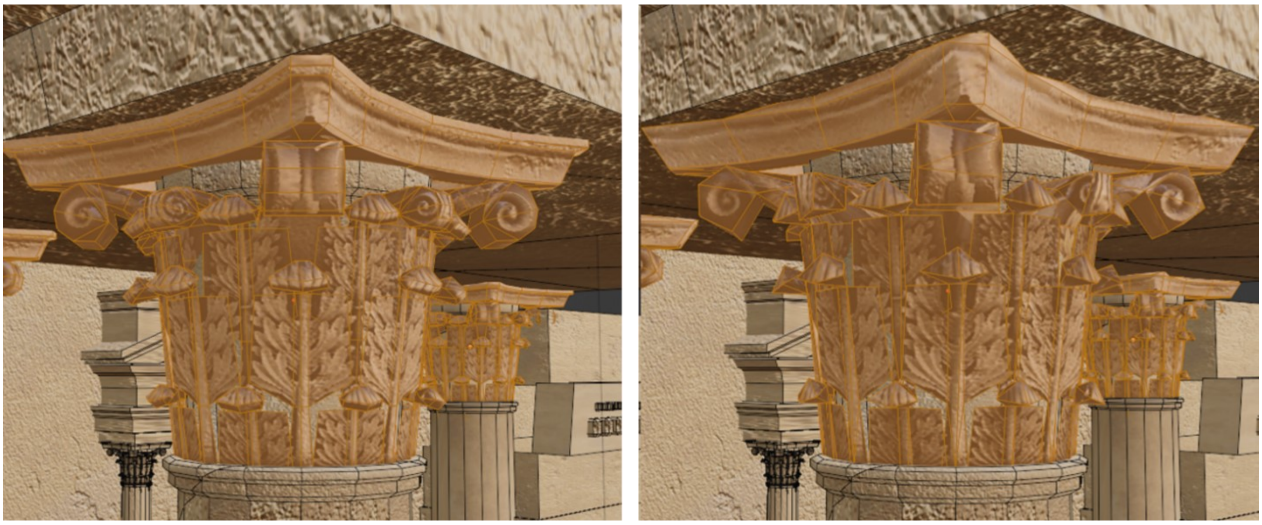


Figure 4: CAD representations reporting the plotting phase: a) Top view; b) Axonometric view; c) Final wireframe view resulting from 9 stations (Ministri, 2015).



(a) (b)

Figure 5: Ornate details optimised: from 4148 vertices (a) to 2436 (b).

This process enabled the graphical reconstruction of all parts of the Palmyra theatre visible in the panoramas. Consequently, the interior was entirely reconstructed down to the smallest details, facilitating precise analysis. The results of this restitution phase for all the visible parts of the theatre are depicted in Fig. 4.

The only exception was the seating steps of the *cavea*, where restitution proved more challenging due to the uniformity of shapes and colour tones, thus complicating the identification of homologous points. After careful analysis and observation, the missing parts were added through mirroring techniques. Regarding the orchestra's pavement, guideline lines were drawn, enabling accurate reconstruction after thorough observation of the panoramas. The remaining parts were reconstructed using a visual virtual anastylosis approach. The results in terms of accuracy are as follows: 64 homologous points were used, with a sigma zero of 0.012 m (obtained with the least squares adjustment computation) and an overall root mean square error (RMSE) of about 0.25 m. The scaling was performed by adding metric information manually measured on site and found in archaeological records (Sear, 2007) for elements of the model.

2.2. 3D model optimisation for VR

The 3D model of the Roman Theatre of Palmyra underwent an initial optimisation process with a conversion to an "all-quad" model. This process converted all triangular faces into quadrilateral faces, resulting in a smoother and more consistent topology. Using the free modelling software Blender v. 4.1, optimisation significantly reduced the number of vertices, leading to faster load times and improved performance, while maintaining the overall appearance and geometry of the model. Additionally, virtual platforms often impose file size and polygon count for uploaded 3D models. Various optimisation tools were employed based on the types of geometry and architectural elements within the theatre's 3D model, ensuring that each object was carefully and meticulously simplified according to its specific characteristics.

For example, more complex elements like capital decorations underwent editing using a tool that compressed square edges to create triangles, while preserving the overall geometry as much as possible. This tool was used in a controlled way, setting the reduction ratio of the number of vertices. In the case of capitals, the reduction parameter was set to 0.5, resulting in a decrease from the initial 4148 vertices to 2436. As can be seen in Figure 5, the geometric details of the ornate parts have been preserved, albeit with a loss of "roundness" in some points, compensated however by the application of a realistic texture. For simpler areas of the model, such as the floor or continuous walls, an editing tool was used to merge coplanar faces. This significantly reduces the number of vertices associated with the pavement.

At the beginning of the optimisation process, the initial vertex count was 489779. Through careful application of these tools, it was successfully reduced to 105221 vertices. Adhering to the 500000 mesh vertex limit demanded by the selected metaverse platform (Spatial, v. 6.50) required essential optimisation. Nonetheless, after importing into the Unity game engine with the SDK, the vertex count increased to 250000 due to different optimisation configurations. Despite this increase, the employed techniques for the mesh simplification ensured the theatre model to be seamlessly uploaded into the Spatial metaverse environment, a step made after the texturing procedure in Unity v. 2023.2.1, as described in the following section.

2.3. 3D model texturing in the game engine

The simplified 3D model of the theatre was exported from Blender in DAE format for integration into the game development engine Unity. The texture refinement process includes a detailed examination of colour, pattern, and surface details based on reference images. One approach involves using tileable textures, which efficiently ensure visual consistency and play a crucial role in simulating real-world materials, thereby enhancing the immersion of the virtual representation.

This process incorporates the integration of various maps (texture and normal map) to enhance material realism, as shown in Figure 6. The primary texture, which provides colour and surface details, is formed by the base map, created through painstaking adjustments based on images of the Palmyra theatre.

In contrast to the height map, which replicates 3D relief on a two-dimensional surface, the normal map adds depth and complex surface features. These maps collectively contribute to a more authentic representation of the Palmyra theatre's texture. Additionally, the occlusion map influences lighting and shadow interactions, enhancing the material's realism by simulating areas with blocked light.

Although using Unity and the Spatial SDK to texturise models within the metaverse platform provides an immersive visual experience, there are inherent limitations. Device performance may be strained by the demand for high-resolution textures, particularly in shared spaces where multiple users interact simultaneously. Real-time transmission of detailed textures may encounter bandwidth constraints, resulting in delays and slower loading times. Achieving consistent texture quality across various devices, such as AR glasses, VR headsets, and laptops, poses challenges due to varying hardware capabilities. Large texture files affect download speed and local storage capacity, imposing constraints on visualisation and storage. Moreover, the complexities of dynamically adjusting textures to lighting conditions can compromise the realism of models.

Ensuring cross-platform consistency demands careful optimisation, and compression techniques employed for performance may introduce visual artefacts. Reduced texture detail in distant objects can affect the visual fidelity of large virtual scenes and managing real-time texture editing issues could lead to inconsistent results. Texture complexity increases when incorporating real-world textures into the metaverse due to additional legal considerations such as licensing and copyright adherence.

Figure 6: Unity 3D scene – Texturing the 3D model.

Figure 7: Unity 3D scene – Virtual exhibition implementation.

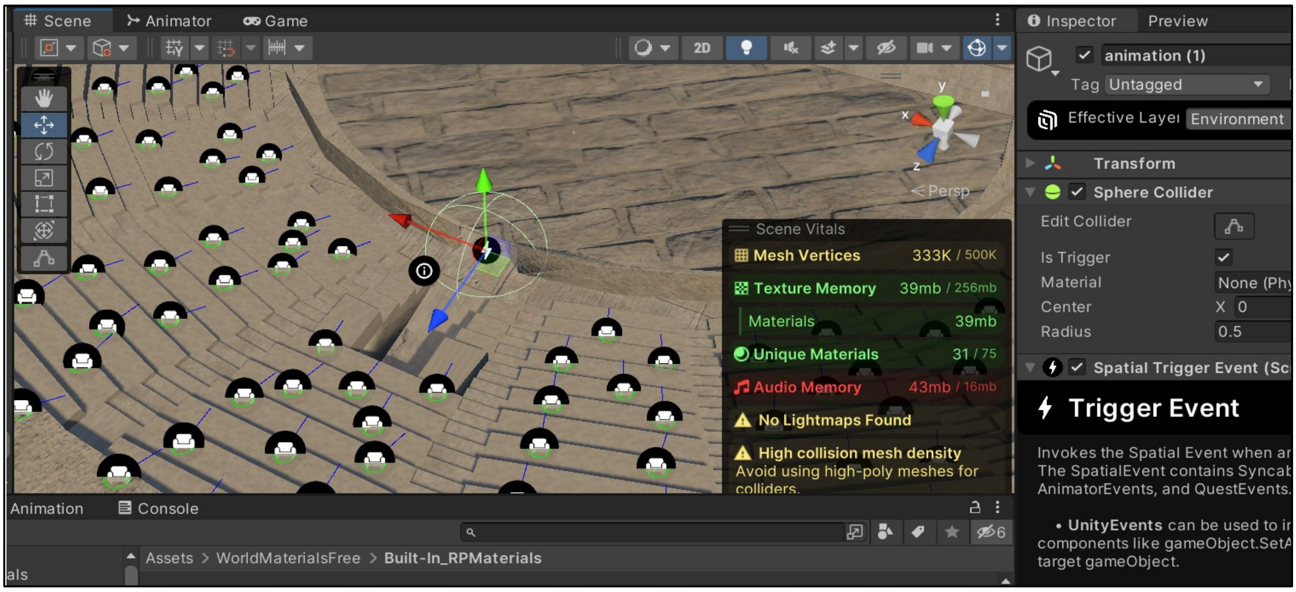


Figure 8: Unity 3D scene – Trigger of the animator event entrance and location of seat hotspots.

2.4. Development of the virtual environment

In developing the virtual environment, it was essential to implement scripts for adding interactive elements and ensuring compatibility with the metaverse platform. Testing and debugging were crucial to ensure everything worked as expected and to resolve any issues and errors. As previously mentioned in Section 2.3, the integration with the Spatial SDK highlights the technical depth and adaptability of the development toolkit.

The complexity and versatility of Unity's tools improved the visual experience, seamlessly extending to the integration with the Spatial SDK. This SDK is an all-inclusive collection of tools, libraries, and documentation designed to simplify and streamline the process of developing software applications. Additional interactive elements were strategically integrated into the environment, leveraging various tools and features within Unity to enhance user engagement.

For instance, a street colonnade was introduced to create an immersive background. Furthermore, additional objects such as trees, stones, and arrows were meticulously added to enrich the landscape. Collectively, these elements contribute to a more immersive and engaging user experience. Additionally, upon entering the designated area, an informational point of interest with a location marker dynamically appears, providing context at the beginning of the experience. A timeline of Palmyra's history was created as a virtual exhibition beside the theatre, featuring photos and descriptive content about the site, as shown in Figure 7.

Moreover, a simulation of the destruction of the main entrance of the theatre's stage was created using Unity's trigger system. These triggers, controlled by enter and exit events, smoothly initiate the animation sequence that recreates the theatre's destruction. By utilising Unity's Animator events, storytelling was enhanced with precise control over the animation sequence.

Furthermore, seat hotspots were implemented in the Theatre *cavea*, as shown in Figure 8, allowing users to interact and sit down in the corresponding virtual location. Using an empty frame script in Unity, sounds were triggered upon user entry and during the simulated demolition, adding a dynamic auditory dimension to the metaverse environment. These empty frames were also used to upload the exhibition images onto the platform. Animation tests were then conducted to ensure that all interactive content ran smoothly for every element of the 3D model.

2.5. Metaverse platform implementation

The 3D scenario, featuring the model of the Roman Theatre, was then uploaded and published on the virtual platform and made available to invited users via a link. Finally, the immersive experience was tested using VR headsets. Stand-alone devices (which do not require connection to an external computer) were chosen for this purpose, such as consumer-grade devices like the Oculus *MetaQuest 2* (with a screen resolution of 1832 x 1920 pixels, a refresh rate of up to 90 Hz, and 6 GB of RAM), to assess the limitations of *entry-level* hardware when exploring complex virtual environments. The headsets proved to be efficient with no bugs or delays experienced during the test, confirming the effectiveness of the 3D model optimisation process. The creation of textures from the images of the theatre ensured a remarkable effect of realism, enhanced by the inclusion of lighting and shadows in scene creation (Fig. 9).

The addition of music to the virtual tour further increased its impact and sense of immersion. Additionally, the simulation of the portico's demolition was successfully integrated into the metaverse platform, and the animation ran smoothly when activated by users at the trigger point (Fig. 10), creating a significant highlight of the virtual experience.

(a)

(b)

Figure 9: Spatial platform, scenes: a) View of the theatre stage in the metaverse environment.

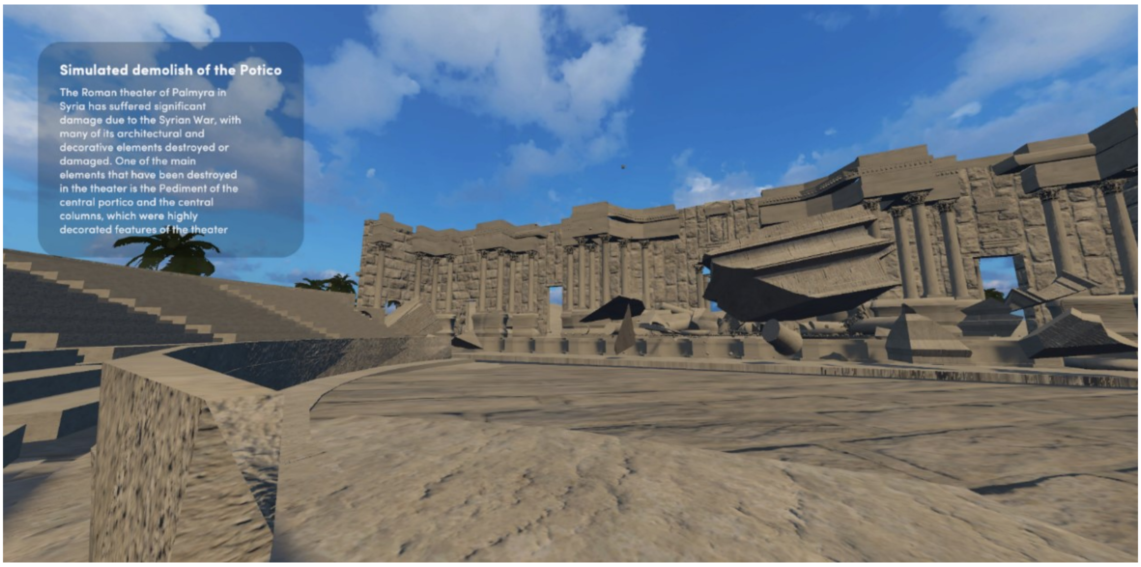


Figure 10: Spatial platform, animations – View of the portico's demolition simulation.

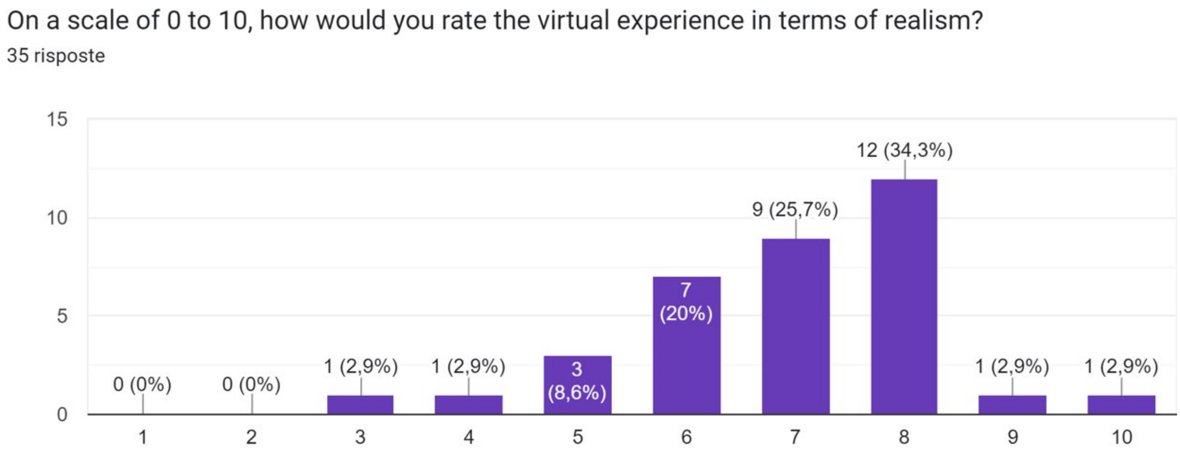
2.6. Users feedback evaluation questionnaire

Palmyra Theatre's virtual scenario , after being uploaded to the metaverse platform, was presented to an audience of 35 users to collect feedback on their experience. The participants were primarily young people, with 80 % falling in the 20-30 age range. They came from diverse backgrounds, including engineering, architecture (80 % were students or PhD candidates), computer science and humanities. The audience was invited to explore the Roman Theatre space using a VR headset, the Oculus MetaQuest 2, and provide feedback by completing a series of questions before and immediately after the experience via an online shared form.

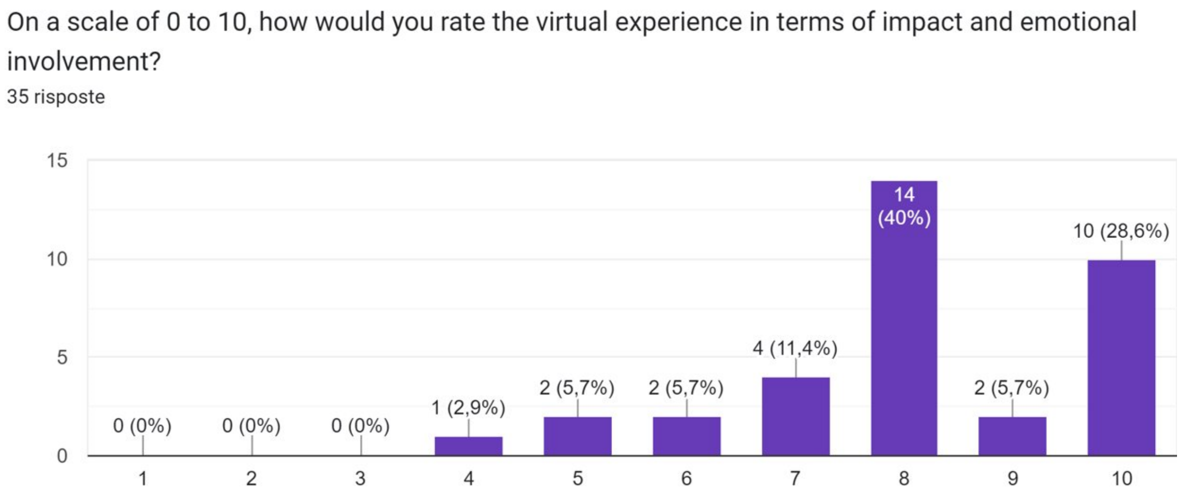
Before the tour, participants were asked questions regarding their previous experiences with VR and the metaverse, their familiarity with the technical equipment, and their knowledge of the historical site of Palmyra. After the tour, participants were asked to provide feedback on various aspects of the experience, including perceived realism, engagement level, and emotional impact. They were also encouraged to share any comments and suggestions to improve the quality of the virtual scenario and overall experience.

The results were compiled into tables and graphs, which were then analysed to draw insights into the strengths and weaknesses of the virtual environment reconstruction methodology developed for this research. Firstly, it was interesting to note that over 40 % of the respondents indicated they had a high level (6-10/10) of knowledge about VR, whereas 35 % rated their knowledge of the metaverse at 1/10. This discrepancy can be explained by VR's established presence over several years, particularly in industries such as gaming, whereas the metaverse remains relatively unfamiliar to the general public.

On the hardware side, instead, 50 % of the respondents declared they were 'confident' in their ability to use VR headsets, while only 20 % reported difficulties in understanding virtual scenario navigation. Regarding the knowledge of Palmyra, on the other hand, 30.2 % of respondents selected 0 out of 10 as their answer, indicating that the site is not well-known among the surveyed audience. With regard to the questions asked after the experience, 34.6 % of respondents indicated 8/10 as the level of perceived realism and 40 % selected 8/10 as the emotional impact of the virtual reconstruction of the theatre (Fig. 11).



(a)



(b)

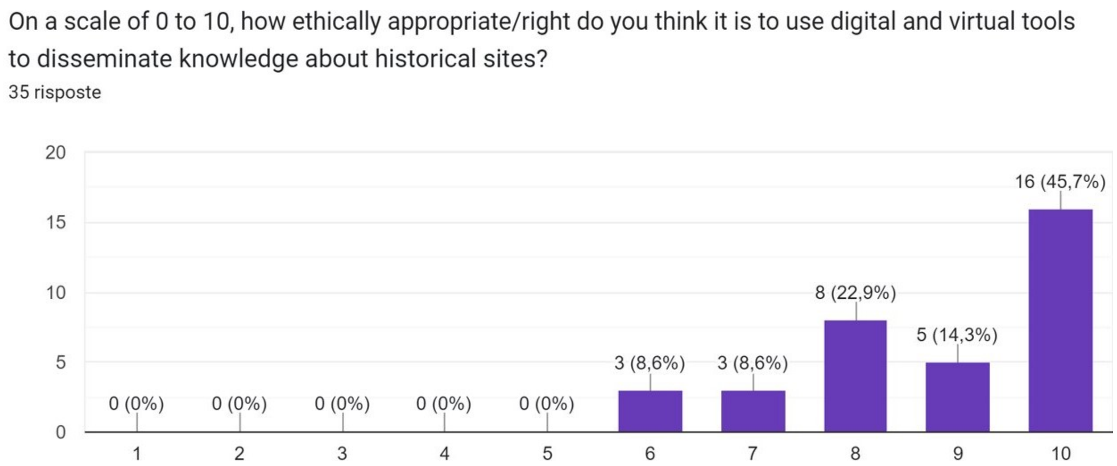
Figure 11: Questionnaire results: (a) answers on level of perceived realism; (b) answers on emotional involvement.

It is interesting to compare these answers with previous responses regarding the knowledge about Palmyra: three people indicated that they had 8/10 knowledge of the site, and of these two indicated "8" as the level of realism and emotional impact, while the third person rated it as barely sufficient (6/10). Only one person stated that they had complete knowledge of Palmyra (10/10) and when asked about the emotional impact, they answered 10/10. This indicates how prior knowledge about the real counterpart of the reconstructed site can trigger two opposing effects: some people probably expect the digital version to convey the same feeling as the physical site, while others are emotionally invested precisely because they know the theatre well and view the virtual tour as a positive opportunity to visit it, albeit in digital form.

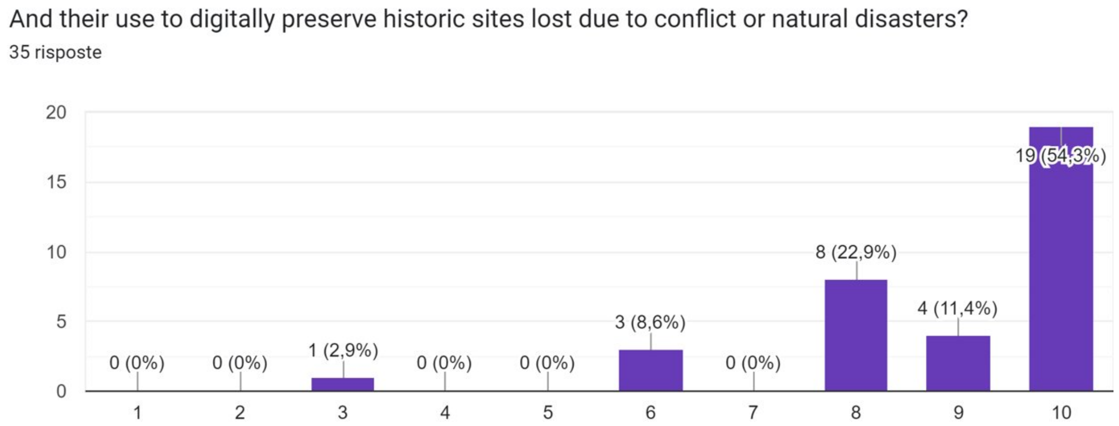
Another interesting response was to the question: *"How useful do you think this type of experience is in gaining knowledge about a historical site?"* No respondent answered less than 7/10. This indicates, as already reported in the literature, e.g. in the review by Khan et al. (2020), that the use of VR/AR tools is perceived as a positive boost for understanding a historical site. The immersivity and fascination these relatively new tools exert on the audience make the learning experience more engaging and thus more effective. In the questionnaire, respondents were also asked about the ethics of using virtual tools in the context of CH in general and for heritage loss due to war or natural disasters.

It was interesting to note that in the first case more than 45 % rated the appropriateness of using virtual tools with 10/10, while in the second case, the percentage increased to over 54 %. These responses suggest that the surveyed public does not consider it ethically improper to use tools such as the metaverse to disseminate information about historical sites. Moreover, they consider it even more appropriate when it concerns places that are no longer accessible in reality (Fig. 12).

Finally, respondents were asked for suggestions to improve the virtual scenario of the Roman Theatre in an updated version. The most frequent responses concerned increasing the level of realism in rendering the virtual environment and incorporating features such as visualising shows and offering guided virtual tours with avatars narrating the history of Palmyra. These suggestions will be considered for future developments of the project. Another observation made by some users concerned feelings of nausea and dizziness experienced during the virtual visit, which negatively impacted their overall experience. This is an issue that needs to be addressed in future updates, leading to considerations regarding the hardware used for the experience. It is possible that the refresh rate of the entry-level VR headset used was not adequate to ensure a smooth experience for some users and improvements may be needed to mitigate motion sickness.



(a)



(b)

Figure 12 Questionnaire results: (a) answers on ethical appropriateness of using virtual tools for CH; (b) answers on ethical appropriateness of using virtual tools for lost CH.

3. Discussion and conclusions

3.1. Considerations on the results obtained

The work carried out for this project highlighted the potential of 3D reconstruction and VR platforms as tools to unearth destroyed CH. The adopted geomatics-VR methodology required significant effort and multidisciplinary expertise. However, it was also demonstrated that free software can be effectively used to reach interesting results for related applications. The meticulous optimisation phase of the model guaranteed a seamless and engaging experience within the reconstructed virtual environment, proving effective even with low-end VR headsets. The results obtained through this workflow suggest that it can be effectively applied to other similar cases.

On the other hand, this project also evidenced the constraints and limitations in terms of available resources in the field of destroyed or endangered CH. Additionally, this work raised theoretical considerations on using digital and virtual technologies applied to a heritage lost due to war. Firstly, ethical aspects emerged regarding the use of these instruments in such contexts. The scientific community working in this field is responsible for adopting technological tools to preserve CH, recognising its significance beyond its material aspects. Nevertheless, the scientific debate on these topics is still scarce (Benjamins et al., 2023).

These formal aspects will need to be studied in depth to understand the extent to which these tools can be used ethically. Nevertheless, the results of the questionnaire highlighted that among the interviewed target group, the use of virtual technologies for lost CH is not perceived as ethically inappropriate. This suggests that, particularly for a younger audience, these tools are perceived as positive and beneficial when used appropriately, especially for lost heritage sites.

Another emerging limitation of using metaverse technology concerns the risk of a shutdown of the virtual platforms due to financial challenges, business decisions, or technological obstacles, as occurred for AltspaceVR in 2023. This poses a threat to the reliability of the virtual worlds where 3D scenarios are uploaded and shared. This raises a paradox about the long-term digital preservation of CH that should be discussed among the academic community using these kinds of solutions. An interesting discussion was addressed in (Huggett, 2020) and in (Cantaluppi & Ceccon, 2022), in which the employment of NFT (Non-Fungible Tokens), blockchain technologies and cryptocurrencies is mentioned as a strategy to guarantee that a virtual CH object is a unique and certified entity. Nevertheless, the current debate about heritage sites in metaverse environment is more focused on legal and economic issues, while the ethical discussion has not been extensively deepened among the scientific community.

3.2. Conclusions

This project is the result of a long process of integrating geomatics and VR methodologies, specifically spherical photogrammetry and metaverse platforms. The workflow employed, in spite of the highlighted limitations, permitted us to achieve the expected result, i.e. the immersive fruition of a lost heritage site. Thus, it can be concluded that the strategies developed were effective and suitable for the purposes of the project, and could be applied to other similar case studies. It was also inferred that this type of technological application is positively evaluated by the sample of users interviewed for the feedback questionnaire, but these aspects will need further investigation. In addition, theoretical considerations emerged, opening the way for ethical reflections about the use of such platforms for the valorisation and dissemination of historical heritage destroyed by war. These issues, too, will require additional efforts in the future by the scientific community. Finally, it can be concluded that this example is a further demonstration of how digital technologies (particularly 3D surveying and geomatics techniques), in combination with virtual ones, can (and should) bring benefits to the CH world , especially when the physical site is inaccessible or, unfortunately, no longer in existence.

3.3. Future perspectives

This work can form the basis for several future developments. Firstly, the techniques and methodologies used in digitally reconstructing the Roman Theatre can be applied and tested on similar case studies of destroyed heritage. From an operational perspective, improvements can be made to the accuracy and realism of the 3D model, as also suggested by some users who responded to the feedback questionnaire.

Other developments could include making an in-depth comparison between the initial model and the optimised version, as well as exploring novel methods of interacting with the virtual environment to achieve a more immersive experience. Moreover, the impact of visiting a virtual site in a shared environment should be investigated further, comparing it with the impact of a tour in a single-user configuration.

As highlighted also by the questionnaire results, a comparison between different VR navigation systems can be conducted to evaluate their effectiveness in improving rendering quality and addressing motion sickness issues. Moreover, future collaboration with experts in the field of heritage communication may be needed to investigate better the advantages and disadvantages of using metaverse/virtual technologies for educational purposes. Finally, the feedback questionnaire can be expanded in the future to a wider and more heterogeneous audience, to collect the opinions of a broader range of users in terms of age, provenance, and educational or working background.

Acknowledgements

This work poses its foundations on the work carried out by Professor Fangi, who spent years of his career on the lost heritage with spherical photogrammetry. Firstly, this work is in his memory. The authors would like to thank all the students who worked on the 3D reconstruction and plotting of several monuments over the years. In this paper, pictures of Palmyra's Theatre original 3D model are from the Master's thesis of Emanuele Ministri, who collaborated in the digital reconstruction in the context of his Master's Thesis at Marche Polytechnic University. We finally thank all the anonymous users who underwent the usability test. The work was partially realised in the framework of the project AlmaAugmented by the University of Bologna.

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