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Bringing back lost heritage into life by 3D reconstruction in metaverse and virtual environments: The case study of Palmyra, Syria

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Abstract. The advent of the metaverse, a large-scale three-dimensional networked virtual environment that combines physical and digital world, has opened new avenues for preserving and experiencing cultural heritage (CH). By integrating technologies such as 3D reconstruction and modelling with virtual reality (VR), the metaverse offers new opportunities to showcase and celebrate cultural heritage that may otherwise have been lost to time or destruction, as in the case of this work. This paper delves into the fascinating world of digital reconstruction and its application in preserving ancient archaeological sites, with a focus on the Palmyra theater in Syria. The theater, dating back to the Roman era, was once a majestic centerpiece of Palmyra's cultural and social life. However, the Syrian conflict caused irreparable harm to the theater's physical structure and historical significance. The goal of the project was to digitally reconstruct the theatre in a virtual environment, providing an immersive experience that allows users to explore the site in its original form. The 3D reconstruction of the theatre was achieved through a comprehensive survey of images, sketches, textual documents, and artifacts conducted by Professor Gabriele Fangi, from *Università Politecnica delle Marche*, Italy, during his visit to Syria in 2010. Metaverse platforms were implemented to allow for exploring the theatre as it once was. The project presented a range of challenges, including optimizing the digital model's complexity for the metaverse, and fine-tuning textures and materials to provide a realistic experience. This paper provides an in-depth analysis of the project's goals, methods, and outcomes highlighting the exciting possibilities of metaverse technologies, allowing multiple users to experience in real time a digitally reconstructed world, demonstrating its importance in the field of CH preservation. For lost heritage, in particular, these technologies may serve as evidence of our duty towards the importance of preserving CH in the face of conflict and destruction.

Keywords: Geomatics techniques · Lost Heritage · Virtual Reality · Metaverse.

1 Introduction

Cultural heritage (CH) sites around the world provide a tangible and intangible link to our past and help us understand the richness and diversity of human history and culture. CH gives a sense of identity and belonging for communities, promotes cross-cultural understanding and appreciation, and contributes to economic growth and sustainable development. Despite its undeniable importance, CH is under threat from a variety of factors, including climate change, urbanization, natural and anthropogenic disasters. Preserving CH is thus a pressing concern and requires a concerted effort from governments, communities, and individuals around the world.

Through historic buildings, we gain a profound understanding of our past and preserve an integral aspect of our CH. When a building is destroyed, it becomes our responsibility to reconstruct it and maintain it as best we can. Unfortunately, the world is currently losing heritage sites at an alarming rate, faster than we can preserve them. However, with advancements in 3D data acquisition and modelling techniques, it is now possible to accurately capture, store, and share the historical memory of built heritage in a digital format. These technological advances provide feasible, portable tools and methodologies that allow for the preservation of heritage sites and the dissemination of cultural knowledge to a wider audience (Fangi, 2015).

Research has shown that virtual environments and metaverse platforms have the potential to significantly enhance learning and retention of information (Hedrick et al., 2022; Hwang et al., 2022; Muenster, 2022). By providing an immersive experience, users can explore and interact with a virtual representation of a cultural heritage site to learn about its history and significance in an engaging and memorable way. Furthermore, the use of 3D reconstruction and optimization techniques can enable the recreation of cultural heritage sites that have been destroyed or damaged (Quattrini et al., 2016; Bitelli et al., 2017). This is particularly relevant in areas affected by conflict or natural disasters, where cultural heritage sites are at risk of being lost forever.

1.1 Lost Architectural Heritage

The preservation of the cultural heritage of a society is indeed considered a fundamental human right, and efforts to protect cultural property in the event of armed conflicts have been established since the 1954 Hague Convention. Unfortunately, in recent years, we have witnessed significant and purposeful destruction of cultural heritage. Bamiyan Buddhas in Afghanistan and Palmyra in Syria are two well-known examples of this phenomenon, as reported by UNESCO, which maintains a country-by-country list of world heritage sites (Fig. 1). Palmyra's Roman Theatre serves as a case study for this research. According to UNESCO, in the previous two years more than 100 ancient structures in Iraq and Syria have been destroyed due to vandalism by various terrorist organizations, and around 56 World Heritage sites are currently in danger of being lost.



Fig.1: UNESCO list of world heritage sites map;
The red dots represent under threat heritage sites - @UNESCO.

Despite the digitization not being able to replace physical monuments, it is widely known that digital replicas are the only way to preserve, at least, their memory. Monuments are not only bricks and stones, but rather represent the identity of a country. Faithful 3D models can be a viable solution to save and preserve their memory.

1.2 Geomatics, Virtual Reality and metaverse for lost Cultural Heritage

The use of digital tools has emerged as a major method of preventing the ultimate loss of architectural heritage. Rapid technological developments, from 3D digital modelling by Geomatics techniques to virtual/augmented reality systems to explore the 3D environments are now available and have given history a fresh lease of life in recent years. Despite physical preservation and restoration being the best approach to preserving cultural heritage, digital technologies can indeed be a powerful tool for preserving and sharing lost cultural heritage. They provide immersive and interactive experiences, allowing people to explore ancient architectures and interact with historical sites and artifacts in new ways.

Over the years, there has been major work on the digital reconstruction and visualization of monuments (Remondino et al., 2009; Barazzetti et al., 2010) that may refer to lost sites due to natural or anthropic reasons. In these examples the digital reconstruction was the final goal of the research, as VR technologies were not widely employed yet in the research field in the early 2000's. Later, virtual reality has been used within museums to engage visitors in the storytelling of collections and as a tool to enhance museum educational content (Hutson et al., 2023). Of peculiar importance has been, for many years, the role of crowd-sourced images for the 3D reconstruction of sites. In (Wahbeh, W. & Nebiker, S., 2017) the authors make a wise comparison of different source of images for the

reconstruction of the lost heritage; unfortunately, this commendable practice never achieved its maturity and the 3D reconstruction is still entrusted on on-site, when possible, and time consuming surveying campaigns.

Examples of exploration of a lost heritage site in VR are also present (yet scarcely) in literature, but they typically employ the VR “standard” configuration, which involves a single user exploring a virtual environment in an individual experience (Chehab & Nakhal, 2023). This solo configuration does not allow for an inclusive or collective experience. Additionally, VR devices often come with high costs that are not affordable for all users. The metaverse addresses these two issues associated with traditional VR. Its fundamental principle is precisely the concept of sharing virtual spaces: users meet in an open environment and have a collective experience. Hence, it is theoretically a shared network of virtual events and locations, in which people meet and interact with avatars in a parallel (digital) universe.

More specifically, the word "metaverse" is a combination of the prefix "meta," which means "beyond" or "transcending," and "universe". The concept of the metaverse goes beyond traditional virtual reality and describes a future iteration of the Internet, comprising persistent, shared, 3D virtual spaces linked into a perceived virtual universe. It is seen as the basis for the next version of the Internet, encompassing all virtual worlds (Moneta et. al 2020, Zhang et al., 2022). The Internet provides the necessary infrastructure for the metaverse to exist, allowing connection, data storage, and participation in its economy. Reliable high-speed internet connections are crucial for a seamless and immersive metaverse experience. In the context of this work, the use of the metaverse is proposed in its general meaning, as it was conceived from the theoretical point of view. However, currently the concept of metaverse has not yet materialized, and for now, there are online platforms that guarantee shared virtual experiences and places with other users, but managed by private individuals and companies that may also have commercial purposes; so, the concept of an open and free metaverse that unites people in a unique networked space is not yet present.

Nevertheless, these online shared platforms (which can also be accessed via desktop versions or mobile devices) provide the opportunity to share digital representations of historical sites, artifacts, and cultural landscapes to be experienced and shared in a virtual community, even if they are physically inaccessible or destroyed. Recently, the metaverse has been also employed in the field of education, as mentioned in the introduction, and in the field of architecture, to document and disseminate knowledge about historic buildings in an educational context (Gaafar, 2021), although primarily focused on existing heritage sites.

Manovich (2021) reported examples of how metaverse platforms can be used for lost cultural heritage, including recreating lost heritage sites, digitizing artifacts, creating interactive and immersive narratives, and enabling collaborative conservation efforts. Metaverse platforms can also facilitate collaborative endeavours to preserve and restore lost cultural heritage sites and artifacts, enabling experts from different parts of the world to collaborate on conservation efforts.

1.3 3D surveying methodologies for Virtual Reality applications

Data acquisition methodologies play a critical role in creating accurate and immersive VR environments. There are several techniques for 3D survey that can be used for VR applications, such as digital photogrammetry or 3D scanning by laser or structured light projection systems. These techniques involve capturing data on the subject's geometry and texture, which are then processed and optimized to create a 3D model suitable for VR.

The instruments employed for a 3D survey are very diverse in their purposes and functions. These include devices that allow to acquire very accurate geometric data designed for small to medium-sized objects, at the micrometre level of accuracy. For large objects or areas other types of instruments are available, such as laser scanners that present long ranges and thus offer the possibility of obtaining geometric information at the architectural level or even over very large areas. The choice of an instrument depends on the needs in terms of precision and accuracy but also on the characteristics of the object to be surveyed from the point of view of size and materials.

1.3.1 Spherical photogrammetry

The methodology, set up by Prof. Fangi (Università Politecnica delle Marche) and used to create the 3D model subject of this research, is the so-called Spherical Photogrammetry (SP), which represent the metrological foundation of the model used in this research. This method (Fangi, 2015) has been tested on several projects, performing the orientation by bundle block adjustment of multiple panoramas (Fig. 2) and finally a manual 3D object reconstruction. The main advantages of this method are the high resolution, the field of view (FOV) up to 360°, the low cost, the completeness of the information, and the high speed of photos acquisition. In contrast, the plotting and the orientation are entirely manual. Nowadays more accurate and efficient tools and instruments are available for CH recording, such as laser scanning and dense multi-view 3D reconstruction. The 3D model of the Palmyra Roman theatre shown in fig. 3 was created with different workflows using SP and sometimes combining it with other photogrammetric-based technologies.

This method was mainly conceived and designed for cultural and architectural metric documentation. Wireframe and then textured models can be created using the aforementioned technique for Syrian monuments, as done in other places around the world. Starting from the SP orientation, there is the possibility to use 3D modellers to create the 3D models based on the rules of projective geometry with a method called panoramic image-based interactive modelling; this technique is suitable for the architectural survey because it is not a 'point by point' survey of the type that dense multi-view 3D reconstruction produces, and it exploits the geometrical constraints of the architecture's geometry to simplify the 3D modelling process.



Fig.2 Spherical panorama of Palmyra Roman Theatre Theatre
by Professor Gabriele Fangi's team

Therefore, the surveyor in those techniques must comprehend the geometry of the architecture before modelling it. In this approach, the concept of this methodology is based on the use of texture-mapping techniques in a generic modelling software as the virtual projector of an image and thus used to model an architectural object. If the projection centre and the orientation are fixed in the 3D virtual space, objects could be created, moved, and modified to match the projections. Objects, therefore, take the right shape and location in the virtual space of the surveyed elements. It is an interactive modelling technique because the interaction between the modelled objects and the projection of the images is visible in real-time. Also, the quality of the model is verifiable in various interactive ways.

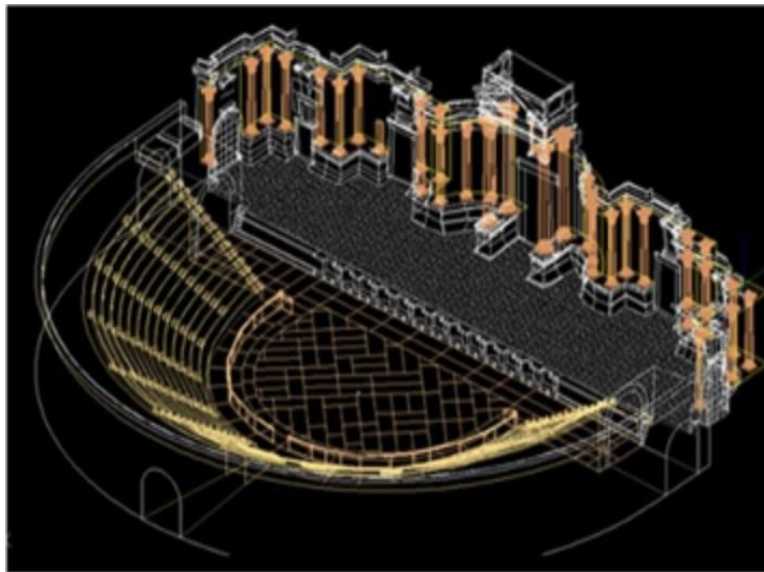


Fig.3 First version of the theatre 3D model obtained with Spherical photogrammetry
(constructed by E. Ministri, Università Politecnica delle Marche)

2 Innovation and objectives of the research

Considering the state of the art of the research in the field of Geomatics, VR and metaverse applied to lost heritage (see section 1.2), in the current literature, a discrete number of examples are reported about the sole 3D reconstruction of lost heritage sites with digital technologies. Few examples are instead reported concerning the employment of VR for lost heritage site exploration, and – to the best of our knowledge - no examples are reported about metaverse applied to a lost heritage site reconstructed with a Geomatic based approach.

The innovative component of this work is the employment of a geomatic method for the reconstruction of a lost architecture (spherical photogrammetry, producing metrically accurate 3D models), coupled with an extensive work of 3D modelling to optimize the geometry and the texture of the model, and finally the virtual exploration in the metaverse to exploit the advantages that this technology may bring to the documentation and dissemination to a wide audience. This approach, employing these integrated technologies for a case of lost architecture, represents an innovation in the field of digital techniques applied to the lost CH.

As outlined in the previous paragraphs, architectural and cultural assets are a fundamental part of humanity's heritage, and all necessary actions should be taken to preserve them. Conflicts and wars have caused priceless losses of archaeological and architectural sites around the world. When "physical" maintenance and reconstruction actions cannot take place or are not easy to be accomplished, digital tools and the virtual world can come into play. The motivation behind this work is precisely to try, through digital technologies, to bring back to life architecture that has disappeared due to war and can no longer be visited anywhere but in virtuality.

The 3D model of Palmyra Roman theatre (obtained with a digital photogrammetry approach from Prof. Fangi's team) has been selected as the case study for this experiment. The main objective of this work is to propose a methodology to merge 3D modelling and VR technologies to promote the preservation lost cultural heritage in a digital environment. The following tasks have been fulfilled:

- To optimize the digital model's complexity, texture adjusting for VR and metaverse platforms.
- To explore the optimization challenges involved in accurately reconstructing the theatre in a virtual environment.
- To create an immersive experience for users using VR in a metaverse platform and to evaluate the outcomes of the navigation with a consumer-grade equipment.

3 Case study: The Roman theatre of Palmyra

Centrally located in the acropolis of Palmyra are the remains of the ancient city's theatre. The construction of the Roman theatre (Fig. 4) along the colonnaded street began in the second century but was never completed. Besides art performances, political meetings were held here as well. Largely buried under sand until the 1950s, the structure has since been excavated and restored,



Fig. 4: The Roman Theatre of Palmyra

representing one of the most well-preserved Roman theatres in Syria outside of Bosra. The theatre was constructed in the first half of the second century according to Polish archaeologist Kazimierz Michalowski. It was built in the centre of a semi-circular colonnaded plaza that opened to the city's southern gate. The theatre has suffered significant damage due to the war in Syria during which several heritage places have been raided (Fig. 5). The territory of the Republic of Syria continues to maintain the same structure of the "historical apparatus", which, in ancient times included the western region of the Fertile Crescent between the rivers Tigris and Euphrates and the Mediterranean Sea.

Along the centuries, populations left their heritage which nowadays stands as existing monuments and ruins, e.g., Phoenician temples, Greek and Roman theatres, and old cities. Early Christians and Byzantines left remains of churches and monasteries; Crusades raised different defensive fortresses. Then Islamic civilisation-built mosques and citadels and introduced architectural elements such as a minaret and a madrasah. In the end, the Ottomans allowed modernization of the country and promoted commercial trade with the construction of *souqs* and *khans*. As stated, the last years changed the archaeological situation of the country due to the war, and the fighting reshaped Syria into different control areas. From the human point of view, this can be considered one of the biggest tragedies happened in the latest period. Beyond this tremendous aspect, the conflict is the main threat to the CH that has faced significant damage from military action, clandestine excavations, illegal civil constructions, and acts of vandalism.

Exploiting the work conducted by prof. Fangi about Syrian lost heritage, many photos (almost 17,000) of most of the Syrian CH monuments were taken during his trip in 2010, before the war. This is a priceless database since it is one of the rarest documentations of this heritage. Most of these monuments are included in the Syrian UNESCO heritage list, and many of them were inscribed in the 'List of World Heritage in Danger' in 2014. With the loss of this heritage as a historical and cultural treasure, future generations were deprived of an invaluable inheritance. A chain of humanity, culture, and nature cannot be violated in 21st century without intervening to save it.



Fig. 5: Destructions of the Syrian cultural heritage during the war in Syria: (a,b) Palmyra, @DW/ BBC; (c) Krak des Chevaliers Castel, @BBC; (d) Umayyad mosque – Aleppo @Reuters

For the Roman Theatre of Palmyra, one of the main elements that have been destroyed is the Pediment of the central portico and the central columns, which were highly decorated. According to UNESCO, the stage back-drop, which was adorned with niches for statues and other decorative elements, was destroyed during the conflict in 2015 (Fig. 5). The actual appearance of the building is therefore lost forever, and it will not be possible for visitors to experience the majesty of this architecture in its original splendour.

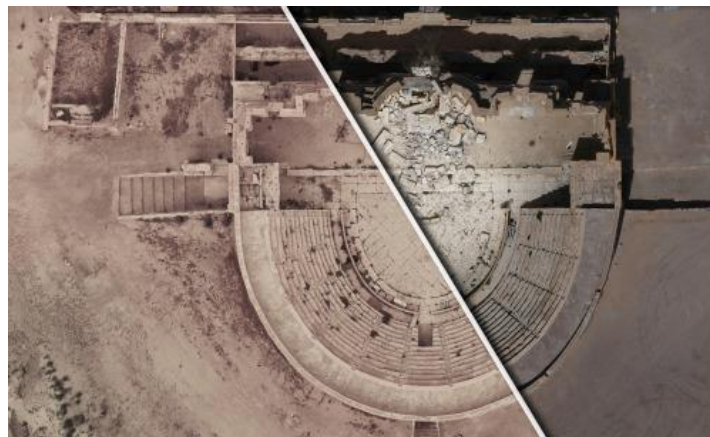


Fig. 6: Orthophotographs of the theatre before and after the attacks @ICONEM

4 Methodology

AEC (Architecture Engineering Construction) professionals have witnessed an epochal change in the previous few years, which has resulted in re-engineering of their daily operations. Simultaneously, VR engines and platforms have provided a completely open logic, allowing for the creation of digital worlds capable of interacting with users via various types of devices using new commands and programming languages, ranging from mobile phones and tablets to the latest generation VR headsets. This section outlines the steps that were taken to achieve the goal of bringing back the lost Syrian heritage through 3D reconstruction in virtual environments, specifically VR and metaverse platforms.

4.1 3D Model of Palmyra's theatre description

The 3D model of the Palmyra is depicted in figure 7. It was initially optimized by converting it into an all-quad model. This process involved the conversion of all triangular faces into quadrilateral faces, resulting in a more regular and consistent topology.

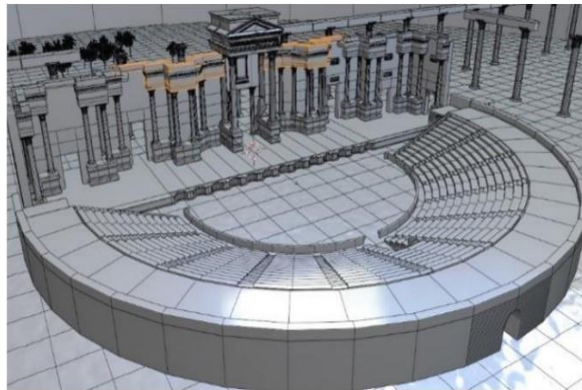


Fig.7: All-quad 3D model of the Palmyra's theatre

The advantages of using an all-quad mesh include smoother surface deformations, better support for subdivision surfaces, as well as more predictable shading and surface deformation when animating, which can make the model look smoother and more natural.

4.2 Data Processing – 3D Optimization

In this research project, Blender open-source software was used to optimize the Roman theatre of Palmyra. Through optimization, the number of vertices can be significantly reduced without sacrificing the overall appearance and quality of the model, leading to faster loading times and smoother performance. Additionally, metaverse platforms often have size limitations for uploaded 3D models, making

them easier to upload and share. Overall, the optimization process of 3D models ensures a better user experience, reduces loading times, and can lead to cost savings in terms of storage and bandwidth.

To optimize the Roman theatre of Palmyra model with an *all-quad* mesh in Blender, three different approach/tool were used: the *Decimate modifier*, the *Limited Dissolve tool*, and the *Decimate Geometry*. All the optimization tools were used according to the different types of geometry present in the 3D model, as shown in the table 1.

Table 1: Optimization tools employed to simplify the theatre’s model.

Tool	Description	Object
<i>Decimate Modifier (Planar)</i>	Reducing polygon count	<ul style="list-style-type: none"> • Cavea • Stage
<i>Limited Dissolve tool</i>	Merging the maximum angle between two faces and the maximum distance between two vertices.	<ul style="list-style-type: none"> • Column • Pediment
<i>Decimate Geometry</i>	Create triangles by collapsing edge loops.	<ul style="list-style-type: none"> • Ornate details • Capitals

To optimize other objects in the theatre, a combination of the *Decimate Modifier Planar* and the *Limited Dissolve tool* or *Decimate Geometry* with *Decimate modifier Planar*, were used, which reduces the number of vertices and edges in a mesh. Using these tools together can be effective but was important to use them carefully and review the results to ensure they met the needs and did not compromise the quality or integrity of the geometric model. As a result of these optimization techniques, the model underwent a significant simplification and streamlining process, resulting in a reduction of vertices from 489,779 to 105,221. This reduction was necessary to meet the constraints imposed by the chosen platform-Spatial, which had a mesh vertices limit of 500,000 for the entire environment. However, when uploaded to Unity with the Spatial SDK, the vertex count increased to 250,000 due to differences in optimization settings, compression techniques, and level of detail generation. By implementing these optimization strategies, the theatre model was successfully prepared for efficient uploading and seamless integration within the Spatial platform. A highly optimized model ensures efficient use of system resources, allowing for the creation of larger, more complex, and interactive virtual environments.

4.3 VR engine – Texture Adjustment

The 3D model of the building was exported in DAE format from *Blender* and imported into the Unity platform. The DAE (COLLADA) format is a 3D asset exchange format that allows seamless and high-fidelity geometry exchange between 3D modelling software. As the photogrammetry process solely captured

the geometric information of the model, the next step was to improve its appearance and reliability by adjusting its texture (Fig. 8). This was achieved through a meticulous examination of images captured at the Palmyra theatre and found online. These images served as a reference for making texture adjustments to closely simulate the real texture of the theatre. Tileable textures were employed as a fundamental component to provide visual consistency and efficiency. The objective was to create a more faithful and realistic representation of the site in the virtual space.

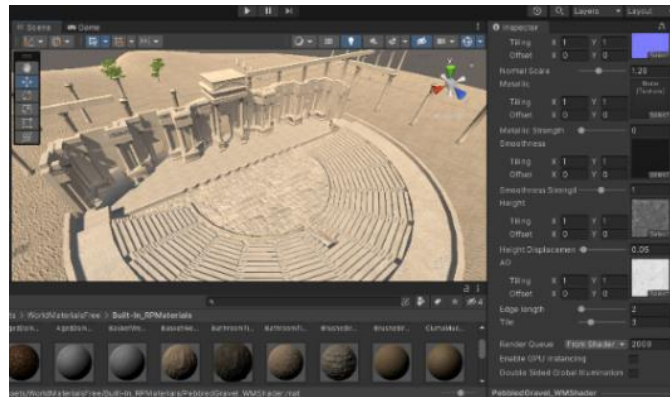


Fig. 8: Unity workflow/ texture adjustment.

4.4 VR Environment - metaverse platform

To create experiences for the metaverse using Unity, a range of tools and features within the engine can be used, such as the Unity Editor, which allows designing, building, and testing 3D environments and interactive elements. Unity's scripting tools are also useful for creating custom behaviours and interactions, as well as integrating with other services and platforms, such as blockchain networks, to add new capabilities to the metaverse experiences. There are several platforms and frameworks specifically designed for creating experiences for the metaverse, offering their own tools and features for creating, publishing, and monetizing metaverse experiences. These platforms often have their own communities and ecosystems of developers and users.

For this research, the Spatial Standard Development Kit (SDK) has been used to import the 3D model from Unity into the metaverse platform. To integrate the SDK into Unity, the Spatial SDK was imported into the Unity project. The Spatial object prefab was added to the Unity scene, and the 3D model of the Palmyra theatre was added. To enable user interactions with the 3D model, scripts were added to the Unity scene. The SDK was then configured to ensure that the Unity scene was compatible with the metaverse platform, including setting the appropriate spatial anchors and establishing communication with the Spatial metaverse servers. Testing and debugging were done to ensure that everything was working as expected and to address any issues that arose.

5 Results and Discussions

This section discusses the outcomes of the project, including the optimization of the 3D model in Blender and its integration into Unity, the use of Unity's scripting tools to enhance the user experience, and the publishing of the model in the metaverse platform using Spatial SDK.

5.1 Optimization Output

The project involves creating a highly realistic 3D model of the Palmyra theatre using Blender, which was optimized to reduce the number of vertices (from 489.779 to 105.875) without compromising its appearance (Fig. 9). The model was exported in multiple formats to ensure interoperability with various platforms and software. The optimization also contributed to the scalability of the virtual environment, allowing for the creation of larger and more complex environments while still maintaining realism. Additional objects were added to the environment after optimization to enhance realism.

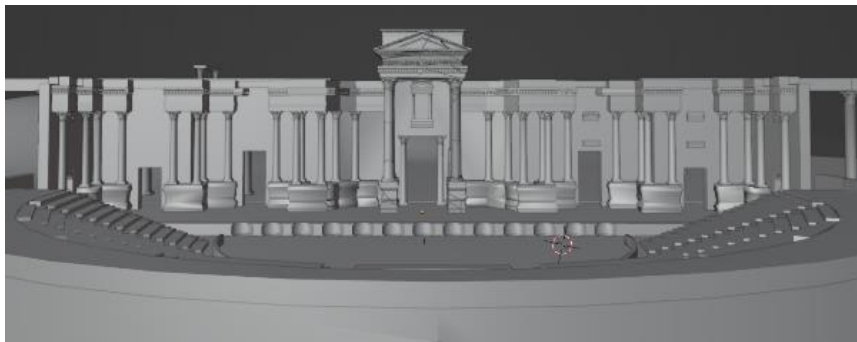


Fig. 9: Blender Workflow/ the final output of the optimization.

5.2 VR Environment

In this step, the realism of a VR environment in Unity was improved by using high-quality textures with realistic patterns and surfaces, as well as normal and specular maps to create depth and accurate lighting. The VR environment is interoperable, using open standards and protocols for seamless integration with other virtual environments. The use of the Spatial SDK allows for publishing on the metaverse platform, enabling collaboration and data/resource exchange for an interactive user experience.

5.3 Metaverse Platform

The metaverse platform offers social features that enable users to interact and socialize in the virtual environment, enhancing its realism. The virtual reconstruction of the Palmyra theatre is highly ubiquitous, potentially accessible from anywhere in the world through the platform using various devices connected

to the internet. The compatibility of the platform with a wide range of devices and platforms is ensured through the use of the Spatial SDK, making it highly accessible to all. The navigation of the model in the metaverse platform was tested with *Oculus MetaQuest 2* headset (see fig. 10 and fig. 11, captured during metaverse navigation in the theatre), which proved effective and suitable for the purposes of this project. Such a simplified model in terms of polygons and the absence of animations and complicated user interactions did not require high-end hardware support, and a consumer grade headset proved sufficient for this first application.



Fig. 10: Final output inside the metaverse platform



Fig. 11: Navigation inside the theatre with an avatar, final output in metaverse platform

6 Conclusions and Future Perspectives

The case study of the Palmyra theatre highlights the potential of 3D reconstruction and metaverse platforms as a tool for bringing back lost heritage. The process of 3D reconstruction, from data acquisition to visualization, is complex and requires interdisciplinary collaboration, but free and/or open-source software can be used to obtain accurate and optimized digital products to be used for similar case studies. Consumer-grade hardware was used to deliver a smooth and immersive experience in the reconstructed virtual environment, ensuring good performance (ensuring that the 3D model is optimized for VR applications as in this case).

This study highlights the importance of exploring and maximizing the use of available resources in virtual reconstruction projects, particularly in a field that faces numerous resource constraints such as lost architectural heritage. The successful application of the methodology presented in this work and the promising results obtained demonstrate the potential for further development and utilization of consumer-grade hardware in lost cultural heritage documentation and dissemination to a wide audience with metaverse platform. This ensures that the tangible and intangible heritage that historic architectures represent is not lost forever, at least in a virtual context.

6.1 Theoretical implications

This work has raised theoretical considerations about the use of digital and virtual technologies applied to heritage lost due to conflict. First and foremost, ethical

aspects have emerged regarding the use of these tools to cases of this nature. The scientific community working in these areas feels a responsibility to preserve cultural heritage through technology, as it carries values that extend beyond their material component. However, the ethical implications of using tools such as the metaverse to disseminate cultural sites have not been explored extensively. These technologies are relatively new and not yet widely used by a broad audience.

Moreover, the platforms on which the metaverse is based are still entrusted on private companies' ownership, having their own rules and policies, even acquiring user data for analytical and commercial purposes. These formal aspects will need to be investigated further by the international scientific community to understand the extent to which these platforms can be used ethically and democratically. Additionally, the potential possibility of platform shutdown presents a drawback when employing metaverse platforms for cultural heritage events, as monetary difficulties, market changes, legal issues, corporate decisions, or technological obstacles may lead to closures. What happens if the virtual platforms adopted for the digital preservation of lost heritage are themselves lost? This raises concerns, and the paradox, about the long-term digital preservation of cultural heritage properties and should be discussed among the scientific community employing such kind of platforms. An interesting discussion was argued in (Hugget J., 2020). NFT (Non-Fungible Token), Blockchain Technologies and cryptocurrencies might be the key to mitigate the risk, even if, nowadays, the attention is more focused on legal and economic aspects of our society, rather than on ethical and societal aspects that lies behind the topic of CH.

6.2 Future research opportunities

There are several potential future research opportunities that could be built upon the work carried out in this project:

- The techniques and methodologies employed to digitally reconstruct a destroyed heritage site can be applied to similar case studies of lost heritage.
- Improvements can be made to the accuracy and realism of the 3D model.
- New ways to interact with the virtual environment can be explored for a more immersive experience.
- Comparison between different VR systems (workstation/headset) can be carried out to evaluate the most suitable equipment to guarantee the best virtual experience.
- Experiments may be conducted with a consistent number of people invited to navigate within the theatre in the metaverse space, and their response regarding the experience will be evaluated.
- Further research is needed to fully understand the potential benefits and limitations of virtual environments for education and learning, and to optimize them for educational purposes.
- The role of Non-Fungible Tokens (NFT) in the context of a heritage digital twin in the metaverse should be explored, to evaluate the possibility to "link" the virtual model to the corresponding real object (Cantaluppi & Ceccon, 2022).

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