REPRESENTING INTANGIBLE CULTURAL HERITAGE OF HUMANITY: FROM THE DEEP ABYSS OF THE PAST TO DIGITAL TWIN AND XR OF THE NEANDERTHAL MAN AND LAMALUNGA CAVE (ALTAMURA, APULIA)

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ABSTRACT:

The Altamura Man and the paleontological remains are situated within a complex context encompassing logistical, geological, paleoenvironmental, and cultural perspectives. This context is exceptionally well-preserved but also fragile, requiring its preservation due to its unique nature. Unresolved inquiries exist in various disciplines, such as archaeology, biocultural studies, ecology, and geology, pertaining to karst formation, taphonomic dynamics, and the cultural and ecological context of the Neanderthal individual found in the cave. Interdisciplinary research was necessary to address these complex questions and understand the broader context of the Lamalunga Cave. Climate change also necessitated attention to preserving the cave's microclimate and monitoring potential biodegradation. Digital technologies, including photogrammetry and laser scanning, were crucial for monitoring and safeguarding the cave's cultural heritage. Digital representation, 3D modelling and Digital Twin were essential for managing the cave's intricacies, analysing its values, and enhancing visual communication. The management of the Lamalunga cave aimed to promote scientific interpretation, safeguard the cave, and provide tools for understanding, storytelling, and further investigation. It was essential to utilise available methodologies and technologies while avoiding destructive interventions. Contemporary technologies have revolutionised the archaeological and paleoanthropological domains, enabling remote study and preservation. Protecting and comprehending the cultural heritage of the cave is linked to its usability, which can be enhanced through digital documentation methodologies to inform visitors about the karst context and promote social and economic development.

1. INTRODUCTION

In recent years, digital representation techniques have revolutionised various sectors, including construction, restoration, archaeology, and tourism, by leveraging innovative forms of virtual museums and projects focused on extended reality (XR), virtual reality (VR), and augmented reality (AR) to enhance information dissemination both on-site and remotely. Through the integration of state-of-the-art surveying and digital representation techniques, it is now possible to create digital worlds where different types of users, ranging from professionals to virtual tourists, can immerse themselves in digital experiences and discover new levels of interactivity and immersion between objects, virtual environments, and associated information. Traditional vector representations such as plans, elevations, and sections are now complemented by digital models that transcend geometric information and effectively communicate material information, architectural history, structural elements, and degradation pathologies. This enables non-invasive analysis and interpretation of the collected data. Additionally, the development of digital twins (DT) is an ongoing area of research and development that holds promise for further advancements. Thanks to continuous technological developments, researchers, architects, engineers, restorers, archaeologists, and anthropologists can expand their knowledge of the digital realm through VR, AR, and the integration of new computer languages such as visual programming language (VPL) and XR development platforms. This transition from static digital models to interactive virtual objects (IVO) capable of responding to user input enhances the digital experience. It facilitates knowledge creation, conservation, and virtual-visual storytelling (VVS). These advancements seamlessly integrate with dissemination tools such as web platforms and novel interactive forms of virtual museums.

The Lamalunga cave complex, discovered in Altamura, Italy, in 1993, is a karst complex known for its in-situ Homo neanderthalensis and paleontological finds. However, it has been investigated partially, primarily focusing on paleoanthropological aspects and secondarily on the archaeology context and karst formations. The interdisciplinary nature of the site necessitates in-depth studies in various fields, including archaeology, geology, and the environment. Furthermore, limited accessibility, logistical challenges, and the need to preserve the internal microclimate restrict visitor access.

Furthermore, the need to preserve the internal microclimate and avoid the excessive introduction of exogenous DNA and the logistical challenges limit access to the cave to experts, precluding the same to the public. To overcome these limitations, monitor ongoing microclimate changes and identify any form of biodegradation in the medium to long term, surveys and 3D digitisation of the karst complex were conducted using advanced laser scanning, photogrammetric, and modelling methodologies. These techniques aimed to facilitate the Scan-to-3D model-to-XR process, generating integrated 3D data through photogrammetry and digital geometric modelling. These models provide architectural, karst, and paleoanthropological insights, promoting new development strategies and knowledge creation in the XR field. In this context, digital transformation and technological advancements have significantly impacted communication within the field of archaeology. This necessitates a thoughtful examination of the innovations that have influenced the design and representation of complex scenarios.

The approach outlined here aims to address the morphological and typological complexity of the archaeological site, striving to develop a process that effectively represents and disseminates its tangible and intangible values. The Science of Representation, Drawing and a detailed understanding of each artefact from a modelling perspective play a crucial role in the generation phase of the semantic model. Drawing and modelling activities are instrumental in managing the site's complexity, costs, timing, performance, and values. Consequently, a comprehensive understanding of the structure and appropriate representation techniques in all their forms is essential for successfully implementing the digital twin and XR experience of the Lamalunga cave.

Figure 1. The entrance of the Lamalaunga cave.

2. THE CONTEXT AND THE RESEARCH CASE STUDY

The cave, located N/E of the city of Altamura in the *Murge Alte*, has been known since 1993 for the presence *in situ* of a Homo Neanderthalensis that can be dated between 172±15 and 130.1±1.9 ka (Pesce Delfino, Vacca 1993a; Pesce Delfino, Vacca 1993b; Pesce Delfino, Vacca 1994; Pesce Delfino 1995; Micheli et al. 1996; Caramelli et al. 2010; Manzi et al. 2010; Lati et al., 2015; Di Vincenzo et al. 2019; Riga et. al. 2020) and more than 500 faunal remains deposited between 45-30 ka (Giacobini, Tagliacozzo, Manzi 2010; Fiore, Cerilli, Tagliacozzo 2018).

The cave, covering an area of approximately 2250 square meters and having a volume of about 1050 cubic meters, exhibits a complex morphology. It is situated within a morphological context characterised by extensive karst formations. The geological succession of the area is referred to as the "Altamura Limestone Formation." (Senoniano Series) (Figure 1) (Agostini 2010). This entrance at 508 meters above sea level constitutes the upper part of a highly evolved epicarp, which in depth refers to different base levels. The complex is mainly composed of two sub-horizontal galleries,which develop at a shallow depth from the surface and depart from a central compartment almost wholly filled with the sediments of a debris cone. Inside are cycles of concretions with different morphologies and mineralogy attributable to varied microclimatic conditions, different air circulation currents, and the geochemical composition of dripping waters (Fig.2). On the surface of the main gallery and in the secondary branches, those mentioned above faunal and paleoanthropological finds are deposited shortly before and after an important phase of collapse (Branca, Voltaggio 2010). In the case of the faunal remains (lying on the surface of various spaces in the cave), the stratigraphic context shows animal bones concretionary on the tabular floor, bones covered by stagnant water, little concretionary bones with a pulverised coating patina, bones embedded or partially adhering to stalagmites and covered by globular inflorescences with coralloid morphology. Instead, the numerous paleoanthropological remains referable to a Homo neanderthalensis in a good macroscopic and morphometric conservation state are still located in the so-called 'Apsis of Man'. This presents an extensive coating of "coralloid" formations generated by the last phase of calcite precipitation and attributable to deposition phenomena, which in some points, incorporate it into the karst formation (Branca, Voltaggio 2010; Vanghi, Frisia, Borsato 2017).

Following the discovery of the paleoanthropological and faunal context, the Lamalunga Cave has been the subject of multidisciplinary investigations aimed at understanding the paleoanthropological remains, the taxonomy of the faunas, the calcitic formations and their dating. In particular, the process of digitisation and semantic representation has allowed, for the first time in the history of the cave, to document and represent with modern digital technologies not only the remains of the Neanderthal man but also 27 animal species.

As part of the protection activities of the Soprintendenza Archeologia, belle arti e paesaggio per la città Metropolitana di Bari in the years 2022-2023, punctual and innovative multidisciplinary investigations and documentation are underway with the need to remotely investigate the entire context from an interdisciplinary point of view (Dellù & Sciatti 2021).

Furthermore, the current and widespread microclimate changes have therefore required new methods of monitoring the entire karst context functional to evaluate any forms of biodegradation of cultural heritage in the medium and long term under the protection of the Ministry of Cultural Heritage, as well as to allow a digital use of these results and of the entire cave, which cannot be exploited on site and therefore directly usable by the public.

3. 3D SURVEY

3.1 Survey workflow

The three-dimensional survey of the Lamalunga cave – the path that leads to the apse of the Man – has the purpose of defining its geometry in a precise and detailed way to reconstruct the digital model. In addition to the cave section discussed earlier, the survey includes the exterior area to mark the locations of the paths and underground chambers and an overview of the limited-access region. The survey was designed following an inspection in September 2022.

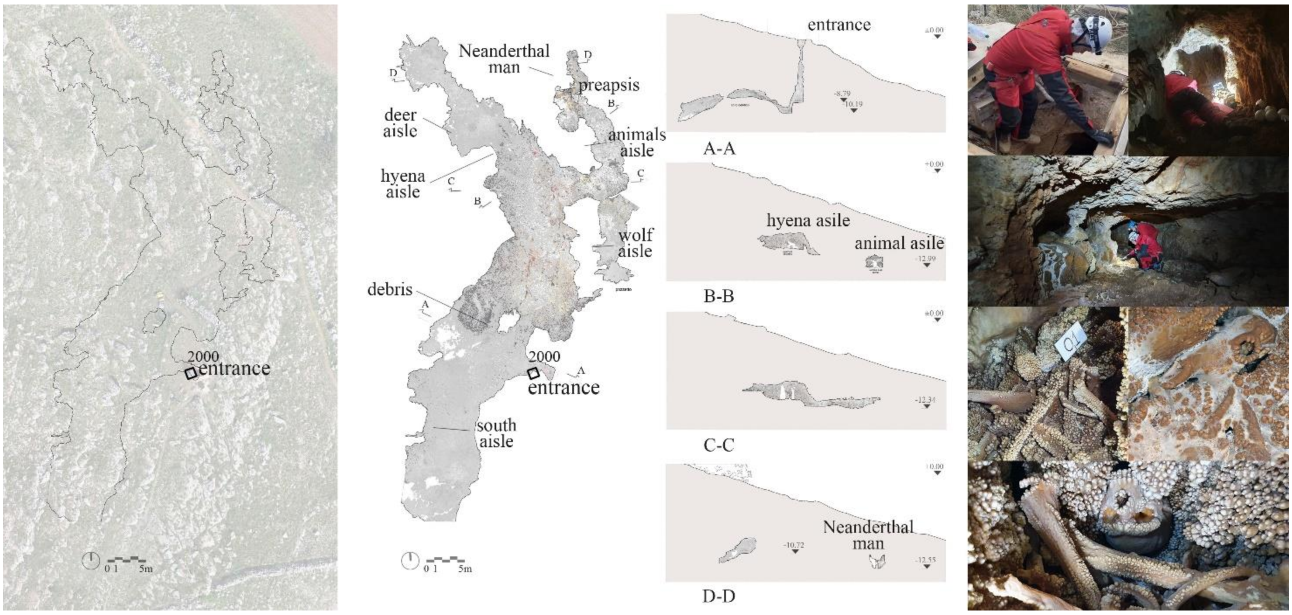

Figure 2. a) Orthophoto, b) planimetry, c) sections, and d) views of the Lamalunga Cave (entrance, animal aisle, some fossilised remains of animals and the remains of the Neanderthal man.

The survey involved several phases. Initially, reference points were established on the surface using GNSS instruments to classify the survey within the National Cartographic System.

A topographic network was created within the cave to serve as a reference system for georeferencing the laser scanner survey. This involved distributing checkerboard targets as control points throughout the cave.

Subsequently, a laser scanner survey was conducted to capture detailed information about the cave’s morphology and features.

Additionally, a detailed photogrammetric survey focused on the man’s apse and areas with other findings, such as animal bones (referred to as ‘fauna’). This survey was aligned with the reference system established by the topographic network, utilising checkerboard photogrammetric targets.

Framework of the survey in the national cartographic system

In the area surrounding the entrance to the cave, 4 reference points (called 1000, 2000, 3000, 4000) measured with GNSS instruments in the static mode were materialised using topographical nails. The survey sessions, measured independently, had a variable duration between 1 and 4 hours, with data sampling at 5 seconds. The static measurements relied on the network of permanent stations in the Puglia region, particularly the Poggiorsini station (POGG). With these measurements, inserting the three-dimensional survey of the cave and the external surface into the cartography was possible.

Determination of a topographic network inside the cave

The topographical network within the cave was established by affixing a series of 8 markers, specifically designed to support topographical targets, to the cave vault using existing anchorages. Measurements were carried out using a Leica TPS1200 total station, starting from 7 station points that formed an open polygonal structure. In total, 28 Ground Control Points (GCPs) were measured, with an average uncertainty of ±5 mm. These 28 control points enabled the georeferencing of the point cloud obtained from the terrestrial laser scanner.

Similarly, 7 GCPs were measured outside the cave (with an average uncertainty of ±4 mm) to georeference the laser cloud obtained from the scanner. Additionally, 11 GCPs (with an average uncertainty of ±4.5 mm) were placed horizontally on the ground to facilitate framing the photogrammetric survey conducted with a drone. These GCPs and the 4 reference points

Using GNSS instruments was crucial in ensuring accurate georeferencing throughout the surveying process.

Laser scanner survey inside and outside the cave

The laser scanner survey was planned to ensure maximum coverage of the cave surfaces with sufficient points density to allow the environment’s three-dimensional reconstruction. FARO Focus 3D X 130 HDR was used for the laser scanner survey. For the alignment of the scans, in addition to the topographically measured GCPs, a series of other spherical targets were distributed in the scene to be surveyed. The same procedure was used for the external part. In total, 121 scans were carried out, divided as follows: 99 scans for the interior, 15 for the external area surrounding the entrance to the cave and 7 scans connecting the interior and exterior; for the internal part, in the areas of most significant interest, colour scans were performed. The connection between inside and outside is the most critical step of the work because access to the cave takes place from a single point, i.e. a small pseudo-vertical shaft. Therefore, the approach followed was to have two separate surveys, one internal and the other external, linked with the scans performed inside the well. To have good reliability in the georeferencing procedure of the two surveys, a sufficient number of spherical targets were distributed inside the well and the scans were performed from a tripod, placed at different heights, in the lower part. In the upper part, the scanner was hung from a structure specially built for this purpose. The scans performed precisely with the scanner in an upside-down position made it possible to detect all the spherical targets positioned in the well correctly.

Framework of the photogrammetric survey of detail

The apse of the man and other areas of particular interest have been surveyed through laser scanning and photogrammetry. To frame these detailed surveys in the general reference system, 30x30mm checkerboard photogrammetric targets were positioned before the execution of the scans. In this way, the laser detected the targets visible in the scans. After the georeferencing procedure of the laser scans, the coordinates of the centres of the photogrammetric targets were obtained, which were then used to georeference the various 3D photogrammetric models.

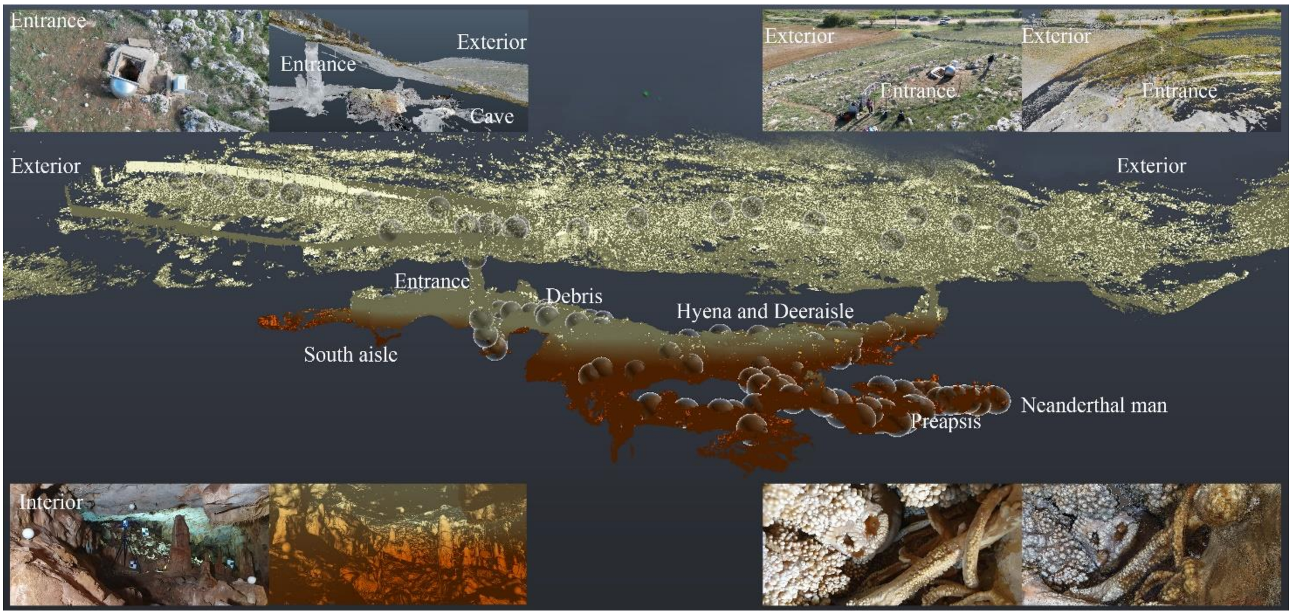

Figure 3. a) The intricate and distinctive morphological features of the Lamalunga cave.

3.2 Photogrammetric survey

The three-dimensional geometric survey of Altamura Cave employed a combination of topographic, laser scanner, and photogrammetric techniques. The photogrammetric survey, in particular, utilised different types of sensors based on the specific descriptive requirements of the surveyed objects. A multi-scale approach was adopted using the same photographic sensor but paired with two different lenses to capture a middle corridor and a narrow burrow where most of the animal bones were located. This established methodology allows for handling objects at varying resolutions within a single photogrammetric project, facilitating the utilisation of three-dimensional data. The walls of the natural cavity were captured from a greater distance using a lens capable of capturing larger surfaces, while the bone remains were captured from a closer distance with a narrower-angle lens to capture finer details. The acquisition process was carried out contextually, meaning that once the survey of the cave geometries was completed, the bone remains were immediately recorded. Ad-hoc photogrammetric targets were strategically placed to ensure proper georeferencing of the detailed surveys in relation to the overall cave survey. Additionally, careful attention was given during the acquisition to incorporate topographic and laser targets, ensuring geometric control and accuracy of the final three-dimensional model. This multi-sensor and multi-scale approach, which has become essential in three-dimensional surveying practices, enables the generation of diverse graphical outputs, including coloured point clouds and mesh models at different resolutions. The results have multiple applications, including on-screen visualisation, generating two-dimensional drawings, managing three-dimensional models through quarriable 3D PDFs, and virtualisation in immersive XR environments. The photogrammetric survey was conducted using a Canon 5DSR camera, equipped with a full-frame sensor and 50.6 Mpixel resolution, a Canon EOS 5D Mark IV, a GoPro Hero 11, professional endoscope Depstech DS300 and a Ricoh Theta Z14K 360°. A Canon 20mm f/2.8 lens was used to survey the cave surfaces, while a Canon 35mm f/1.4 lens was used for the bone remains. To compensate for inadequate artificial lighting, two synchronised shooting flashes were employed to ensure sufficient diffuse light, even in the most remote areas of the environment.

This operation produces a medium-resolution three-dimensional textured model for the identified sections of the cave. Additionally, it generates 11 highly detailed models of the processed bone remains in the form of 3D PDF documents and high-resolution textured mesh models. These documents are designed to be easily shared and managed, even by individuals without prior experience in working with three-dimensional data. Furthermore, high-resolution orthophotos are created for each point of interest, including the interior and exterior of the cave. This comprehensive approach allows for accurate digitisation and metric analysis of both the cave itself and the bone remains.

4. THE DIGITAL RECONSTRUCTION OF ALTAMURA CAVE AND NEANDERTHAL MAN

Given the current state of conservation, fragility, and complexity of the archaeological site, a dedicated consultancy program and studies were undertaken to update and enhance the existing knowledge framework. This program focused on conducting a comprehensive 3D survey and digitising the entire context, encompassing the cave, anthropological, and faunal remains at a high resolution. To achieve this, advanced 3D survey techniques and modelling were integrated to facilitate a Scan-to-3D model-to-XR process. The objective was to generate 3D data that seamlessly integrates photogrammetry (both aerial and terrestrial) and digital geometric information. This approach allowed for the creation highly detailed and accurate 3D models that could be managed at architectural, archaeological, and bone remains scales without compromising the site’s integrity or omitting any crucial details.

The consultancy program aimed to capture the site’s essence while leveraging advanced technologies to create a digital representation that accurately reflects its intricacies. The incorporation of photogrammetry, both from aerial and terrestrial perspectives, ensured a comprehensive and detailed dataset. The resulting 3D models provide a manageable and navigable framework for architectural, archaeological, and bone remains.

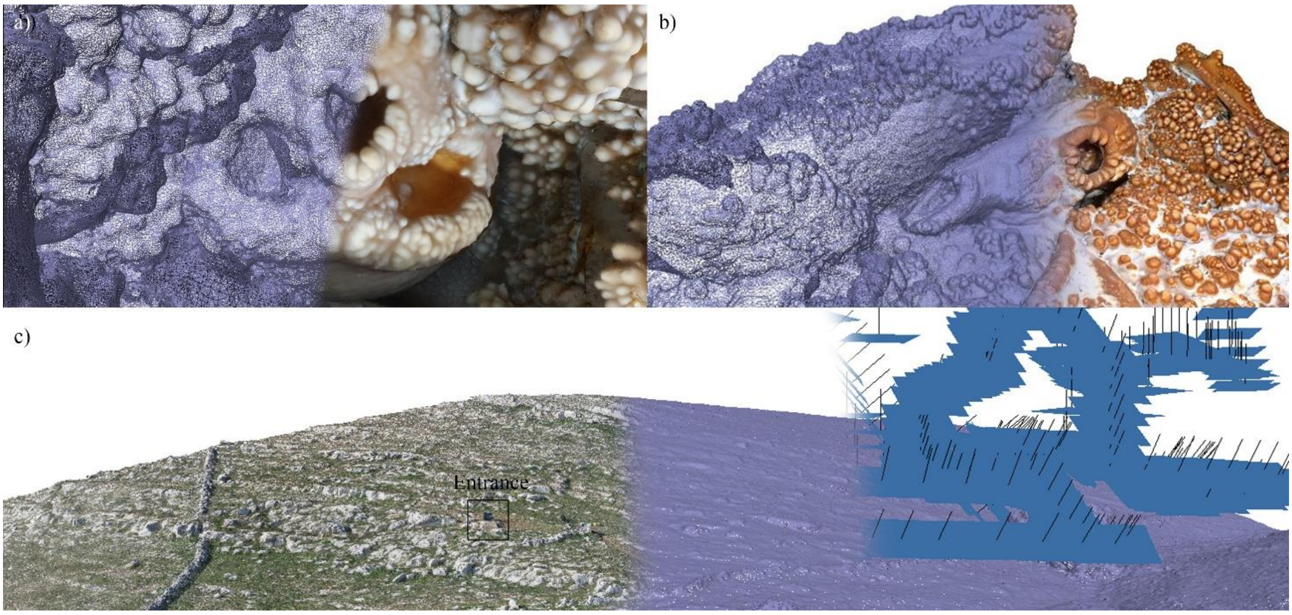

Figure 4. a Some of the most significant photogrammetric outputs consist of millions of high-resolution polygons and textures. These include: a) the Neanderthal man, b) animal remains, and c) the externally georeferenced context.

In addition to describing the techniques used for digitising the site, the article shows the results obtained inthe field of digital representation showing how the models have been used to support its usability in a virtual environment, to be managed as an experimental DT aimed at supporting a multidisciplinary and multi-platform environment. In the domain of 3D modelling, it is widely recognised that the conversion of point clouds into mesh models presents certain limitations for the subsequent utilisation of the model in XR environments. The main challenge arises from the physical characteristics of the mesh model, which hinder the recognition and effective utilisation of these entities. The discrete nature of polygonal meshes results in a certain level of approximation when representing three-dimensional objects. While planar objects can be accurately represented, curved objects require higher precision, leading to an increased number of faces and vertices in the mesh. As a consequence, this demands greater computational resources and memory allocation. The high polygon count in mesh models derived from laser scanning or photogrammetry results in large file sizes, often exceeding the memory capacity of XR applications. Therefore, optimising the polygon count is crucial for proper visualisation and efficient model utilisation. This poses challenges when converting 3D modelling applications into interactive virtual objects (IVOs). To address this challenge, retopology is commonly used to create low-resolution models that serve as a foundation for more complex models. Retopology allows for managing the object’s overall shape using fewer polygons, improving model efficiency. This process is necessary when the original model does not meet project requirements, requiring comprehensive optimisation. Retopology also considers the topological aspects of the polygonal mesh, particularly the arrangement of faces, to ensure suitability for subsequent stages like texture mapping. Texture mapping enhances the visual appeal of the model using image-based techniques. On the other hand, the decimation process primarily focuses on reducing polygonal complexity without addressing topological characteristics. Polygonal meshes are used to break down three-dimensional objects into simpler geometric elements, with triangles and quadrangles as the predominant shapes.

Among these shapes, triangles offer several advantages as they are planar and convex, making simpler surface normal calculations, colour interpolation, and shading computations. Additionally, hardware algorithms for rasterising triangles are highly efficient. On the other hand, quadrilaterals lack consistent planar or convex properties, which makes calculating normal vectors and handling linear relationships more complex. Rasterising quadrilaterals requires more computational time compared to triangles. However, quadrangular meshes are often preferred due to their ability to facilitate texture mapping, animation, and the inclusion of intricate details. Tetrahedral meshes are highly suitable for applications that demand flexibility and adaptability to the object’s shape. They excel at accurately representing complex shapes and enable the delineation of regions of interest. However, their employment entails elevated memory requirements and intricate manipulation and generation procedures. Thus, the mesh type selection hinges upon the specific needs of the application at hand. The central focus of the modelling process revolved around developing a virtual reality-augmented reality (VR-AR) prototype aimed at facilitating in-depth remote analysis of bone surfaces and calcitic concretions within the designated context. The primary objective was to spatially map these elements’ distribution, consistency, calcite detachments, organic material degradation, and anthropometric measurements (Fig. 5 & 6). To accomplish this, the digitisation process extensively used XR environments, seamlessly integrating the modelling environment with NURBS/mesh techniques and XR development platforms. This integration fostered the creation of immersive experiences centered around one of the most historically significant archaeological sites. This phase demanded a meticulous approach, relying on a comprehensive understanding of the artifacts through archival research, interpretation, and rendering within a digital environment. While digitisation has gained considerable prominence in digital representation, balancing traditional practices and future-oriented opportunities has assumed paramount importance. The effective utilisation of both digital and traditional forms of representation proves indispensable, underscoring the holistic value of the digital representation as a potent knowledge tool during the modelling phase.

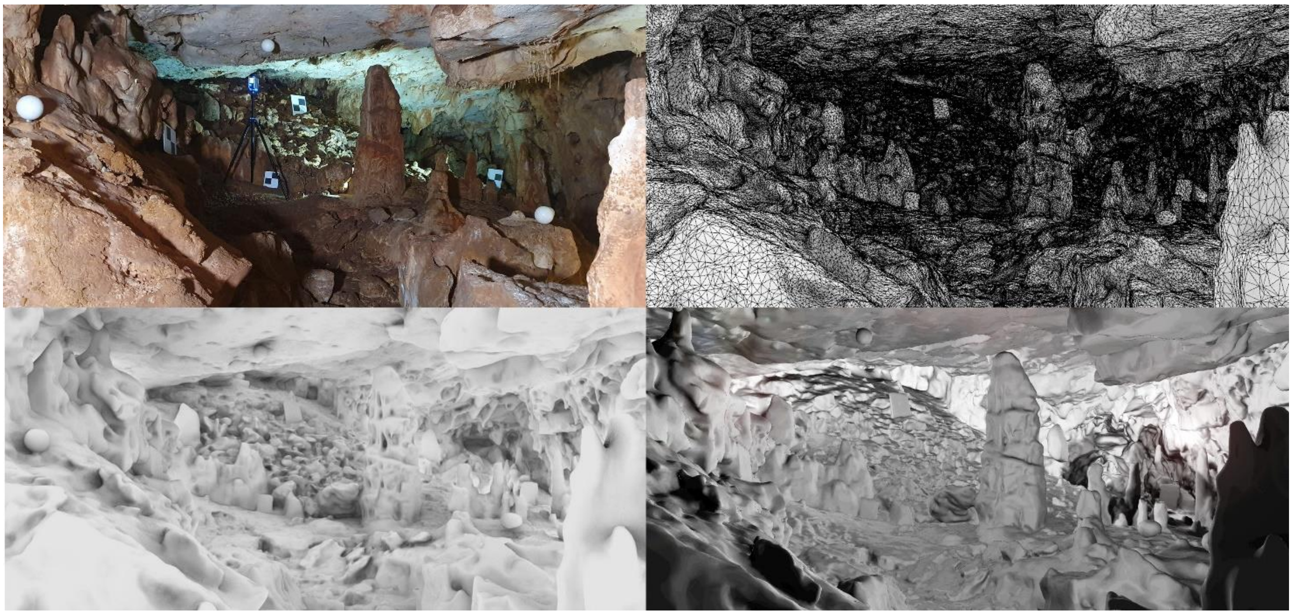

Figure 5. The 3D model of the Lamalunga cave: from mesh to NURBS model.

This recognition enables the exploration, creation, and management of meaningful relationships between forms, materials, and spaces.
Identifying, analysing, interpreting, and comprehending "unique" artefacts and materials were pivotal in achieving accurate and semantically rich three-dimensional representation. The primary objective was to attain high levels of detail (LOD) and information (LOI) in the models by decomposing them into sub-elements capable of representing semantic entities beyond the geometric attributes of the cave.
The graphic works combined survey drawing with interpretative 2D and 3D synthetic drawings, meticulously examining archival and bibliographic sources alongside the current state of the cave and its bone remains (Fig.7).
Abundant data derived from laser scanning and photogrammetry facilitated dimensional and formal-compositional accuracy. Subsequently, this foundational information was processed to create digital models that faithfully embody the critical intentions underlying reworking the studied and analysed sources.
The creation of intelligent parametric objects constituted a crucial phase in mapping information and sharing intricate scenarios related to bone remains reliably (Fig.8).
The combined 3D modelling techniques and NURBS algorithms effectively addressed the generative gap within XR platforms. The application of specific modelling requirements and Grades of Generation (GOG 9 and 10) enabled the creation of interactive models that went beyond mere replicas or virtualisations of reality, serving as heuristic tools to support users in the Scan-to-3Dmodel-to-XR process (Banfi & Mandelli, 2021).
The digital modelling process requires interdisciplinary connections with various fields, ranging from heritage conservation to disseminating tangible and intangible values associated with the cave and the bone remains.
Exploring innovative and efficient solutions such as VR and AR provided immersive and captivating experiences for visitors, enabling them to fully comprehend and appreciate the historical and cultural richness of the archaeological site at different scales.

5. DIGITAL TWIN AND EXTENDED REALITY

In the realm of heritage preservation, the Scan-to-BIM process still requires multiple applications and exchange formats to obtain digital models that can be seamlessly navigated, controlled and shared. In this context, adopting a holistic approach that leverages advanced 3D tools while minimising reliance on numerous exchange formats (both proprietary and open) can offer an effective solution for representing and disseminating the intrinsic values of built heritage.
This approach aims to enhance the overall sustainability of the preservation process and reduce potential information loss throughout different stages.
Through the application of innovative APIs (Application Programming Interfaces), models can be directed towards a new form of digitally shareable representation, exemplified by the concept of Digital Twins (DTs) and web-XR platforms.
Digital representation and visual communication have been investigated with the aim of making semantic models effectively showcase associated information in the best possible way.
The development of a WebXR platform has proven to be a valuable tool in enhancing the visiting experience of the Altamura cave.
Through the use of a visual programming language (VPL) for avatar development (in both first and third person), interactive environments, and objects, representation and user engagement have become increasingly immersive and personalised, offering significant opportunities and research perspectives in the fields of representation, education, and communication.
As demonstrated through practical experiments, this innovative and engaging approach has enabled sharing of our history and cultural identity with a broader audience through interactive digital representations, where a human-centric approach defines the rules and relationships established between the user, virtual environments, and their respective contents.
In this scenario, it is essential to understand the available technologies to enhance the visitor experience by distinguishing between each technology's different levels of interaction.

Figure 6. The NURBS model of the Lamalunga cave: the animal aisle and the entrance of preapsis.

Applications, totems, multimedia boards, multi-user touch tables, and video mapping are the main tools for improving the enjoyment of multimedia paths, but they are considered low-interactivity and low-immersiveness tools. In contrast, cutting-edge VR and AR technologies enable new levels of interactivity, where virtual visitors can immerse themselves in "*dynamic*" environments and acquire knowledge, archival materials, and storytelling, offering new opportunities for virtual representation. In recent years, one of the main applications proposed in VR and AR is the integration of new devices and tools such as Microsoft Hololens and Oculus Quest, which can take users to new levels of immersion and interaction.

Thanks to these innovative technological advancements, a phase of experimentation in the XR field has been initiated to enhance the Level of Interaction through increased interactions between models and users. The research case study has been directed toward virtual visual storytelling (VVS) of its historical, cultural, and biological background. Content, geometry, and dynamics are the three fundamental elements that could define an interactive experience and make it unique. Content comprises objects and associated information within the environment, forming the foundation of the virtual experience and can be manipulated by the user through specific input devices. Geometry in a virtual environment defines the physical appearance, including the layout and size of objects and their positioning in three-dimensional space.

Dynamics refer to the interaction rules among the contents within the virtual environment, including interactions between objects and the user. The aim of well-designed dynamics is to make the virtual experience as realistic as possible, enabling users to interact with virtual cultural heritage similarly to how they would interact with real-world archaeological and anthropological finds. Consequently, proxemics should be investigated to define desired relationships.

Furthermore, the development phase of an interactive experience consists of the following steps:

- Definition of virtual-visual storytelling (VVS),
- Definition of content-geometry relationships through digital proxemics,
- Development of an Avatar and definition of Navigation and - Interaction modes based on a human-centric approach,
- Development of interactive environments and objects (IVE-IVO),
- Integration of Visual Programming Language (VPL),
- Three-dimensional mapping,
- Multimedia outputs,
- Final development and packaging.

Virtual-Visual Storytelling (VVS) employs advanced 3D graphics software to create immersive three-dimensional environments, facilitating the organisation of scene elements and thematic focuses, such as bone remains and the Apsis of Man, with the aim of captivating the user's attention.

The primary objective of virtual environment creation is to deliver realistic and interactive experiences, necessitating meticulous management of the spatial relationship and interaction between the user and virtual objects, particularly within cave formations' intricate and confined spaces.

Proxemics, a concept borrowed from the field of human interaction, plays a pivotal role in comprehending how users engage with space and objects in virtual environments. By studying proxemics, designers can enhance the design and usability of the virtual environment. Defining appropriate interaction areas between the user and virtual objects is crucial to ensure an optimal user experience, preventing excessive divergence, particularly during instances that require close interaction.

Adapting the distance between the user and virtual objects enables the desired emotional effects while mitigating the risk of collisions. Moreover, users should be able to navigate freely within the virtual environment while receiving adequate support for effective proxemic management.

Information points strategically placed throughout the virtual environment serve as guides, offering a "backtracking" feature that assists visitors who may become disoriented or lose track of the narrative thread. Visitors can conveniently resume their immersive experience and regain their bearings within the virtual environment by selecting specific windows that frame the thematic focuses. These features contribute to a seamless and engaging virtual-visual storytelling experience.

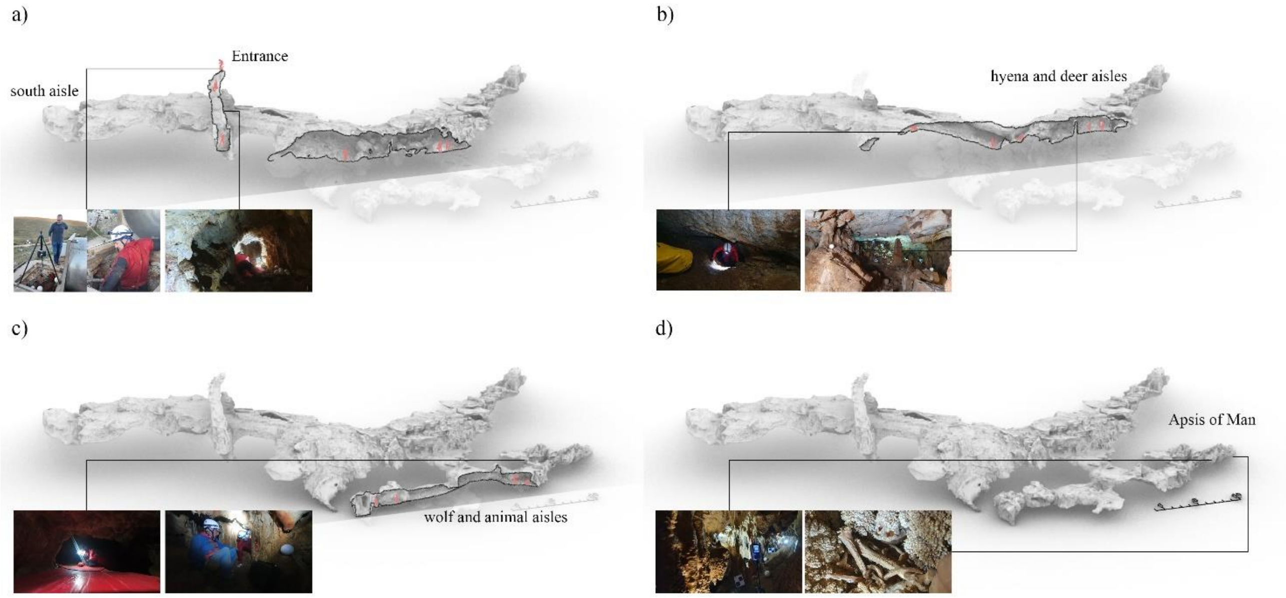

Figure 7. The NURBS model of the Lamalunga cave: from the entrance to Apsis of Man. a) the entrance, b)the largest space, c)the wolf and animal aisles and d) the apsis of Man.

In virtual reality experiences, using both first and third-person perspectives can significantly influence user immersion and the perception of the cave environment, providing them with a choice in their final experience. Designing virtual environments and interfaces that maximise user interaction and immersion is crucial to crafting engaging virtual experiences. Adopting a human-centric approach necessitates a comprehensive understanding of user needs, preferences, and limitations.

Consequently, the XR project involved creating a navigable environment accessible through various devices, enabling users to select the most suitable mode based on their capabilities.

VR headsets, mobile devices, and PCs can be interchangeably employed for navigation, contingent upon the user's interaction and immersion preferences. Navigation via an avatar in an Interactive Virtual Environment (IVE) and interaction with Interactive Virtual Objects (IVO) constitute pivotal elements for heightening the user experience and enhancing levels of interactivity and immersion. In this context, Visual Programming Language (VPL) emerges as a fundamental tool for scripting and incorporating interactivity into XR projects.

VPL has demonstrated promise as an alternative to the cave's XR experience, particularly for individuals who are not proficient in conventional coding. It empowers authors to develop computer applications through a visual interface based on an interconnected graph of elements following a node-based logic. This simplified approach facilitates the transition from static models to dynamic objects, allowing for the association of specific behaviours with each element in the scene. Consequently, direct or indirect interaction with the user is facilitated through the avatar.

Notably, most XR development platforms support scene processing and the production of a range of multimedia outputs that seamlessly integrate with the XR environment.

These outputs include renderings, panoramas, presentations, sequences, and 3D animations. Rendering and 3D animation present opportunities to integrate the developed VR/AR environment as authentic Interactive Virtual Objects (IVO), enriching the Interactive Virtual Environment (IVE). Upon concluding the XR project development process, due consideration must be given to the distribution phase of the application, which can be executed on diverse platforms, such as PCs, consoles, and mobile devices.

The Unreal Engine provides a comprehensive suite of built-in tools, including the packaging function, which streamlines the development process by creating executable packages for distribution. Customisable configuration options such as screen resolution and graphic quality settings can be applied through the packaging function. Once packaged, the application can be distributed through various channels like websites or popular platforms such as Steam or Apple's App Store.

Additionally, the emergence of the Web XR API has expanded the possibilities of virtual and augmented reality experiences. Platforms like Twinmotion and Unreal Engine enable the adaptation of VR and AR environments into web-based products. Web XR technology allows for immersive experiences directly within web browsers, eliminating the need for separate app downloads. Users can access interactive experiences on a range of devices, including VR headsets, smartphones, or tablets. This versatility and accessibility make Web XR technology suitable for creating immersive experiences across different devices and platforms.

Consequently, the development of a Web XR environment for the archaeological site serves as a fitting conclusion to this study. The focus has been creating an interactive environment that ensures seamless navigation, even on mobile devices. Users can choose between different devices, such as mobile devices or advanced VR headsets, based on their capabilities and preferences. A portable interactive environment has been developed through cutting-edge cloud technology, enabling users to engage with Interactive Virtual Objects (IVOs).

This immersive experience culminates in the meticulous exploration of the well-preserved Neanderthal remains, accompanied by a diverse repertoire of multimedia components, including dynamic 3D animations, auditory features, audiovisual presentations, immersive 360-degree photographs, and globally recognised visual documentation (Fig.9).

The seamless integration of these captivating elements has played a pivotal role in the formation of an interactive representation of unparalleled efficacy, adeptly recounting the profound narrative of the Lamalunga cave and the ethereal qualities it harbours, transcending temporal boundaries and echoing through the vast expanse of approximately 150,000 years.

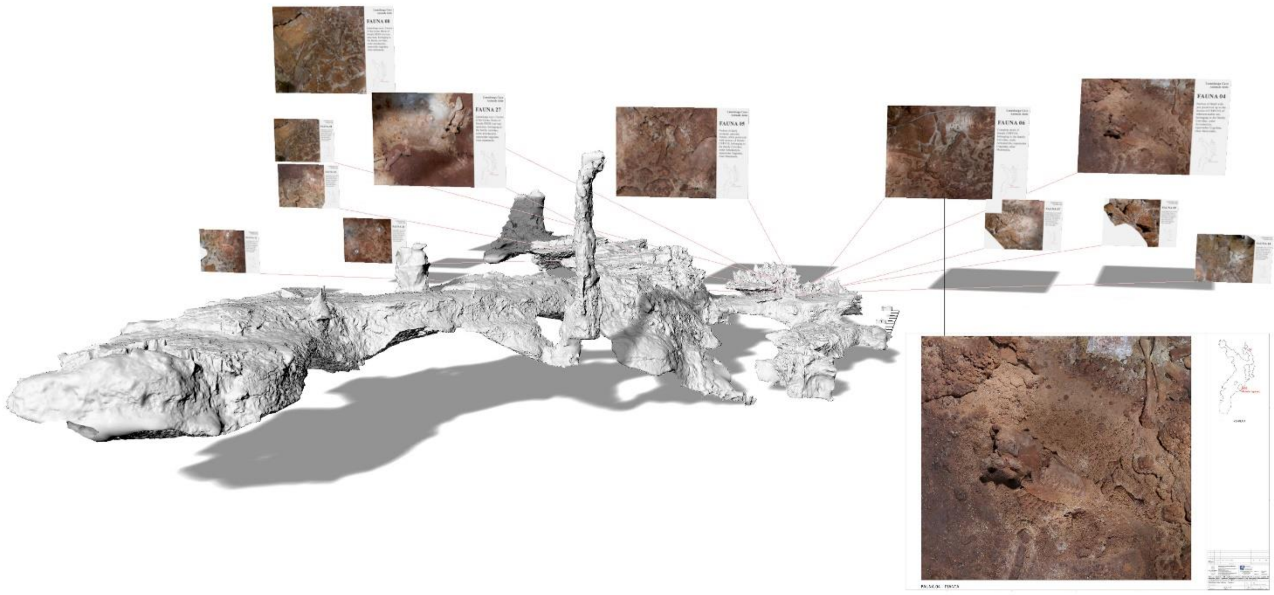

Figure 8. The model has been enriched with the inclusion of animal remains models. Each contribution can be selected and viewed in its correct location in 2D (drawings) and 3D (textured models).

6. DISCUSSION AND CONCLUSION

The Altamura Man and the paleontological remains are situated within a highly intricate context, encompassing logistical, geological, paleoenvironmental, and cultural perspectives.
This context is remarkably well-preserved and exhibits exceptional fragility, necessitating its preservation due to its uniqueness.
From the standpoint of archaeology, biocultural studies, ecology, and geology, numerous unresolved inquiries persist, each pertaining to specific areas of expertise. These encompass a comprehensive understanding of karst formation and subsequent natural events that have shaped the current configuration of the cave, as well as the taphonomic dynamics and spatial positioning of the faunal remains.
Additionally, investigations into the peri-mortem events that led to the presence of the Neanderthal within the so-called apse of Man, coupled with targeted archaeological inquiries, previously unexplored, hold the potential to contribute to a more comprehensive definition of the ecological and cultural context in which the individual lived and died.
These complex questions can only be addressed through highly interdisciplinary research that extends beyond the Neanderthal skeleton to encompass the entirety of the Lamalunga Cave and its broader external and surrounding context. Such research endeavours offer a comprehensive perspective that transcends disciplinary boundaries. Simultaneously, the significant global climate changes necessitate heightened attention to implementing access procedures to preserve the cave's microclimate, characterised by nearly constant temperature and humidity.
Additionally, monitoring potential forms of biodegradation that could impact the internal karst environment is crucial, enabling the adoption of functional conservation measures. In this regard, alongside ongoing microbiological analyses directed by the Superintendence, the utilisation of new digital technologies showcased here proves instrumental in monitoring the cave and safeguarding its cultural heritage for public purposes. Notably, the integrated application of digital photogrammetry and laser scanning of the last generation has facilitated the development and implementation of an approach capable of transforming point clouds and meshes into a virtual environment, enabling interaction with cutting-edge platforms such as Web XR.
Digital representation, encompassing graphic, infographic, and multimedia language, has emerged as an indispensable tool applied across 2D, 3D, and XR dimensions. Its significance lies in effectively managing the morphological and typological intricacies of the Lamalunga cave, analysing existing values, and enhancing visual communication.
Under the auspices of the Superintendence, the cultural heritage management endeavour at the Lamalunga cave pursues dual objectives. Firstly, it aims to promote the study and scientific interpretation of this extraordinary multidisciplinary context. Secondly, it assumes the responsibility of safeguarding the cave and delivering it, along with the necessary tools, to the present and future community, enabling understanding, storytelling, and further investigation.
Conducting research within this context necessitates the utilisation of all available methodologies and technologies in the current landscape. It involves avoiding destructive and irreversible interventions that could result in the loss of multivariate data, contingent upon the outcomes achievable through interdisciplinary investigations led by specialists in their respective fields.
Contemporary technologies employed in research offer increasingly precise and sophisticated tools, as observed in the progression from the discovery of the Altamura Man in 1993. Their expanded application in the archaeological and paleoanthropological domains has revolutionised the field, enabling remote study and preservation of complex contexts.
Lastly, the imperative to protect, preserve, and comprehend the cultural heritage inherent in the Lamalunga cave is intrinsically linked to its usability, albeit mediated by new technologies. Visitors can be informed about the diverse and numerous facets influencing the karst context through the employed digital documentation methodologies.
This promotes an informed utilisation of the complex heritage spanning millions of years, with the overarching aim of engendering virtuous social and economic development processes.

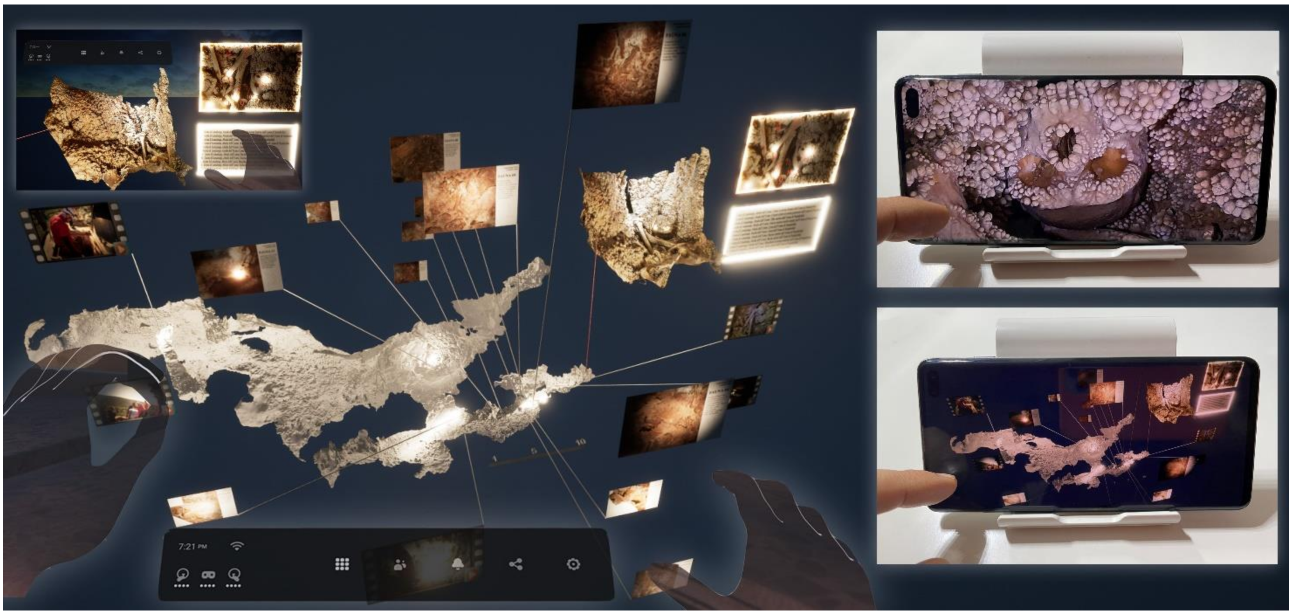

Figure 9. The digital twin and the extended reality experience of Lamalunga Cave.

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