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VIRTUAL ACCESS TO HERITAGE THROUGH SCIENTIFIC DRAWING, SEMANTIC MODELS AND VR-EXPERIENCE OF THE STRONGHOLD OF ARQUATA DEL TRONTO AFTER THE EARTHQUAKE

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Abstract

Interactive representation has proven to be an effective tool in various disciplines related to Digital Cultural Heritage (DCH). This study proposes a research method that uses interactive representation to share complex scenarios like the Stronghold of Arquata del Tronto, facilitating novel forms of heritage dissemination. The scan-to-BIM process made it possible to digitise complex structural elements damaged by the 2016 earthquake. The investigation of the complexity paradigm improved the reliability of the semantic model that supports the preservation process. Interoperability and accessibility paradigms were explored to create a more comprehensive and accurate understanding of the built heritage. A web-VR platform was developed to enhance user interaction and simplify virtual environment exploration without using complex hardware (VR headset and controllers), making it possible to experience VR in the browser.

Keywords

Interactive Representation, Drawing, Virtual Reality, Arquata del Tronto, Web-VR Platform.

1. *Introduction*

In recent decades, one of the primary challenges in Digital Cultural Heritage (DCH) has been establishing shared guidelines and standards for storing, sharing, and disseminating information. The goal was to ensure remote access to cultural heritage while preserving associated data and metadata, ensuring scientific transparency, and addressing copyright issues. Technology has significantly impacted the daily activities of professionals involved in the building life cycle, providing new 3D scanning tools and advanced research methods to handle large volumes of data and enhance the accuracy of architectural representations.

Concurrently, government organisations have introduced new standards and, where possible, made them mandatory to convey the levels of development, detail (LOD), and information (LOI) in digital models. Several nations have encouraged and subsequently adopted supranational standards like ISO to ensure the quality of these novel digital representations. In December 2018, ISO 19650 was approved, and it became a European standard (EN) in 2019 for all member states through the direct adoption mechanism of the Vienna Agreement. This standard was conceived to embody the state of the art, practice, and shared knowledge among all stakeholders (both private and public) of a specific process, service, or product.

However, insightful studies have highlighted the main limitations of these guidelines, which primarily focus on new constructions, and have proposed methods to enhance HBIM projects from both geometric and informational standpoints (Bianchini, 2014; Brusaporci et al., 2012; Ippolito, 2015). Today, most European Union member states where BIM is not yet obligatory require urgent integration of the Scan-to-BIM process into their standards and guidelines to better refine and specify the levels of development, detail, and information of their built heritage.

The increasing recognition of the value of HBIM models emphasises developing proprietary and open formats that can represent the geometric information of the built heritage and effectively communicate and share its semantic richness. This emphasis is closely tied to identifying a generative approach capable of fully harnessing the value of Drawing as a knowledge tool, fostering the creation of more comprehensive, precise, and interoperable Historic Building Information Modelling (HBIM) models. In this context, adopting and defining new methods capable of accurately representing semantic models constitute a crucial element in improving information sharing during restoration and, more broadly, throughout the building's life cycle.

Remarkably, the success of these new forms of representation depends on their ability to convey both geometric and semantic information, enabling a better understanding of the built heritage and more efficient management of analysis, maintenance, and restoration activities.

The definition of appropriate methods and formats should not be regarded solely as a technological challenge. Still, it should be approached broadly and interdisciplinary, involving professionals from diverse fields and integrating innovative communication and information-sharing approaches (Osello, 2012). Only through such an approach can we fully leverage the benefits offered by HBIM models and make the most of the opportunities presented by technology to enhance quality and promote interoperability across various disciplinary sectors.

The methodology employed in the case of the Stronghold of Arquata del Tronto exemplifies this type of research. The study aims to provide access to one of Arquata's primary heritage buildings, which was damaged by the earthquake that struck Central Italy in 2016 (Fig. 1). The research was conducted following the execution of a contract between the Department of Architecture and Urban Studies of Politecnico di Milano (Prof. A. Grimoldi, Prof. A. Landi) and the Municipality of Arquata del Tronto, initiating the initial building assessment and conservation plan for the Stronghold and the church of S. Francesco in Arquata del Tronto.

2. *Research objectives*

In recent years, thanks to the benefits observed even for newly constructed buildings (Eastman et al., 2011), the Scan-to-BIM process and HBIM have been significantly improved to preserve the built heritage. HBIM is a specialised extension of Building Information Modelling (BIM) that focuses on documenting, conserving, and managing historic buildings and cultural heritage sites (Murphy, McGovern & Pavia, 2013).

Fig. 1: The Stronghold of Arquata del Tronto with its main architectural elements after the 2016 earthquake . The bastion on the left and the tower on the right.

It involves the creation of a digital model that captures the physical characteristics, historical context, and relevant information of a historic structure or site (Galera-Rodríguez, Angulo-Fornos & Algarín-Comino, 2022; Bruno & De Fino, 2021). By combining BIM principles with the unique heritage conservation requirements, HBIM integrates diverse data types such as architectural plans, survey data, historical documents, and conservation guidelines into a cohesive digital model (Gargaro, Del Giudice & Ruffino, 2019).

The primary objective of HBIM is to support informed decision-making and facilitate the preservation and management of historic buildings. By creating detailed and accurate virtual representations, HBIM enables professionals to analyse the structural integrity of heritage sites, simulate conservation interventions, track changes over time, and document their historical significance (Rocha et al., 2020). HBIM models serve various purposes, including conducting condition assessments, planning restoration projects, assessing risks, creating interpretive and visualisation materials for public engagement, and ensuring long-term maintenance and monitoring (Hussein & Ismaeel, 2020).

One of the significant challenges in the contemporary HBIM domain revolves around managing and making a substantial volume of data available. Seamless communication between databases and 3D models often encounters difficulties due to differing standards and purposes, resulting in limited accessibility to associated information. Data fragmentation hampers the realisation of a comprehensive and unified compendium based on standardised methodologies, thereby impeding the full potential of emerging technologies in organising and sharing knowledge.

This research aims to make the information, acquired data, and tangible and intangible values of the Stronghold accessible, as it is currently inaccessible due to severe damages caused by an earthquake in Arquata. Through innovative forms of representation, various tools are employed to disseminate content by combining visual data with information (Ferretti, Quattrini & D'Alessio, 2022; Giordano, Russo & Spallone, 2021; Cannella, 2021; Agnello, Cannella & Geraci, 2022).

The Stronghold's fluctuating fortunes, transitioning from a military base to abandonment, have encompassed both moments of brightness and darkness for the building.

However, the earthquake and subsequent reconstruction process have completely disrupted the "life cycle" of the Stronghold, rendering it inaccessible to the citizens of Arquata. Consequently, digitisation aims to achieve innovative dissemination through state-of-the-art representation techniques like virtual reality (VR) (Trizio et al., 2019; Lasorella, Cantatore, & Fatiguso, 2021; Beltramini & Gaiani, 2018). Moreover, using models and databases, the digital representation of built heritage adapts to diverse forms of analysis, ranging from conservation projects to developing new storytelling approaches, thereby ensuring data accessibility in professional and educational domains (Sdegno et al., 2015; Guidi, Russo & Angheleddu, 2014).

For those reasons, the authors conducted a comprehensive digital survey encompassing 2D and 3D representation in 2019 and 2022. This research involved various tasks, ranging from archival research to the formulation of a conservation plan, as well as the 3D survey and the development of digital models and representations to support the restoration process and the dissemination of tangible and intangible values associated with the research case study. The research was carried out through the following sequential steps and objectives:

- Archival research involved a meticulous and comprehensive exploration of historical records and documents specifically associated with the Stronghold. This rigorous investigation delved into primary sources, such as ancient manuscripts, letters, official reports, and other archival materials, aiming to extract valuable insights and information regarding the historical context, events, and individuals associated with the Stronghold. The process entailed meticulous examination, analysis, and interpretation of these sources to construct a detailed and accurate understanding of the Stronghold's historical significance and evolution over time.
- 3D survey: The 3D survey phase entailed the proficient utilization of a diverse range of cutting-edge techniques, including total station, TLS scanner (Terrestrial Laser Scanning), and photogrammetry. These advanced methodologies were employed to capture and record highly precise three-dimensional data of the Stronghold. By leveraging total station technology, precise measurements of spatial coordinates were obtained, ensuring accurate positioning and dimensional information. Additionally,

photogrammetry techniques were deployed to capture high-resolution imagery from multiple angles, facilitating the creation of realistic and accurate textured models.

- 2D and 3D representation: Utilisation of acquired data to create detailed two-dimensional and three-dimensional infographic representations.
- HBIM model: Development of a Historic Building Information Modeling (HBIM) model, incorporating geometric and semantic information to create a comprehensive digital representation of the Stronghold.
- 3D modelling of access paths: The creation of three-dimensional models illustrating the pathways leading to the Stronghold enhances the understanding of the site's spatial context.
- Preliminary conservation plan and guidelines: Formulation of a preliminary plan outlining the necessary actions for conservation, including material analysis and mapping of decay patterns.
- Development of VR and Web-VR projects: Implementation of VR and Web-VR projects to enhance user interaction and provide immersive experiences related to the Stronghold. The final step of this study aims to define a comprehensive research approach, fostering a multidimensional understanding of the Stronghold's historical significance and supporting its preservation and knowledge dissemination.

3. The Stronghold of Arquata del Tronto

The Stronghold of Arquata del Tronto boasts a fascinating and intricate building history that can be traced back to the 12th century. It stands as a testament to the medieval defensive system prevalent in the Ascoli Piceno province. Throughout the years, the construction of the Stronghold has undergone various transformations, including the loss of its defensive purpose in the latter half of the 18th century. In the 1990s, extensive restoration works were carried out to revive the entire structure, breathing new life into the Stronghold. However, the tragic earthquake of 2016 inflicted significant damage, causing a setback in the preservation and revitalisation efforts for the fortress. Despite this setback, dedicated endeavours are underway to overcome the stagnation by implementing innovative strategies integrating preservation and landscape design, ensuring a brighter future for the Stronghold.

3.1 Historical background

The Stronghold is perched atop a hill, commanding a panoramic view of the village of Arquata. Situated at the border between territories with diverse histories, economies, and administrations, it lies between the Sibillini and Laga mountains. Arquata's economic prosperity in both the Roman Empire and Middle Ages was intricately linked to the Via Salaria. This ancient Roman road served as a vital link between the Adriatic Sea and Rome, the empire's capital. Moreover, the village's strategic location allowed for control over the Galluccio pass, granting access to Montegallo and Norcia. Although the construction of the Stronghold commenced towards the end of the 11th century or the beginning of the 12th century, discerning the structures of its initial settlement presents a challenge. One prominent feature of the Stronghold is a square donjon, measuring approximately 7x24 meters, which is believed to be one of the earliest components of the fortification system (Fig. 2).

Fig. 2: The Stronghold after the 20th century restoration and damaged by the 1940's earthquake (?) (top); The Stronghold and Arquata in an old postcard (bottom) (Ciancotti, 2018).

Although it may date back to the mid-14th century, no documents citing its presence allow us to distinguish the preserved remains. The initial defensive wall was extended to the south, forming a secure space, before additional walls were erected to create a rectangular courtyard. At the north-western side stands the donjon, while the polygonal bastion (8x8m) occupies the southeastern corner, and the circular bastion is located on the southwestern side. The western defensive wall continued over the donjon, although only a portion still stands today.

Historical records of the Stronghold are limited, and insights into its construction phases can only be gleaned from a study of its structures. Maintenance work is documented after the 1703 earthquake, but the Stronghold ceased to function as a defensive structure by the mid-18th century (Petrucci, Lapucci, & Lapucci, 2020). Archival research indicates that the Stronghold underwent restoration works during the 19th and 20th centuries, albeit with varying degrees of accuracy.

3.2 Post-earthquake building assessment

The Stronghold of Arquata del Tronto underwent 20th-century restoration and was assessed through two surveys to evaluate earthquake damages in 2016. Employing investigative methodologies to gather data is crucial for understanding deterioration mechanisms, material decay, architectural attributes, and finishes (Grimoldi Landi & Adami, 2023). Vertical sections highlight instability and reveal anomalies related to prevalent stone masonry construction practices. Merely observing the structural decay of the Stronghold is insufficient; proactive measures must be taken to address the underlying causes that have resulted in varying consequences from the same seismic event. Preliminary inspections indicate that the earthquake damaged inadequate additions, repairs, and preventive systems. Neglected sections lacking maintenance and proper waterproofing significantly compromised the wall's integrity. The southwest corner of the defensive wall exhibits a common instability mechanism characterised by corner overturning. This phenomenon is exacerbated by imprecise construction techniques used during the reconstruction of over half of the masonry in the 1990s, which failed to establish adequate connections with the existing walls (Facchi et al., 2021). No subsidences are observed as the towers and walls directly rest on the emerging rock at several points. Sections closest to the foundation remain mostly intact, indicating stable and homogeneous support. Visual inspection reveals no significant damage to the embankments in front of the donjon and the east and west walls. The external wall of the defensive structure displays varying degrees of expulsion in different sections.

This phenomenon is particularly prominent in areas with inadequate conservation conditions, including eroded mortar joints, degraded stone blocks, previously reconstructed portions, and upper vegetation. The root system of the vegetation contributes to a "wedge" effect, detaching the external facing. Understanding decay mechanisms, architectural features, and finishes within the Stronghold necessitates a comprehensive investigation of construction phases, restoration interventions, and maintenance activities. Detailed geometric surveys and vertical sections serve as invaluable analytical tools when integrated with other relevant information, enabling the interpretation of damage and informing effective restoration practices.

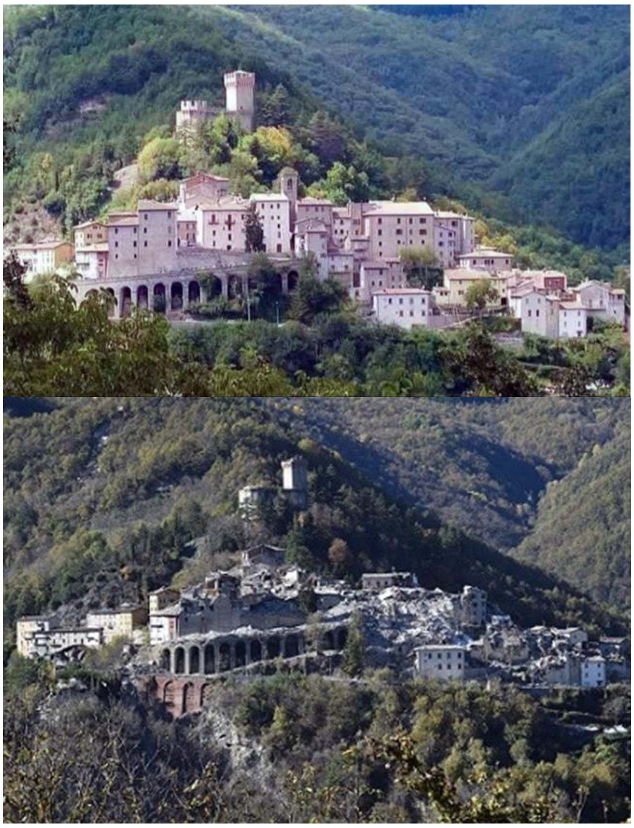

Fig. 3: The Stronghold and Arquata before (top) and after (bottom) the 2016 earthquake.

The seismic event caused significant damage to inadequate additions, repairs, and prevention systems, compromising the structural integrity of the walls. Vulnerable areas, previously repaired or rebuilt, experienced concentrated damage from recurring earthquakes.

Specifically, the battlements of the donjon, reconstructed in the first half of the 20th century, collapsed due to inadequate connection and clamping between their parts. The metal structure connecting various masonry sections in the courtyard also contributed to localised instability where it contacted the walls. On October 21, 2020, the Municipality and the group of engineers and architects signed a contract outlining the reconstruction design plan for Arquata del Tronto.

The reconstruction project prioritises the territory's safety, preservation of the built heritage, and incorporates innovative and anti-seismic construction methods to enhance the historical tradition, image, and collective memory of these locations.

3.3 Digital survey

The fortress underwent a geometric survey during two campaigns: one in May 2019 and another in September 2022. Due to the damages and difficult accessibility caused by the earthquake, a geodetic network combined with laser scanning was utilised to ensure the robustness of the acquired data. The network consisted of 9 landmarks and was measured with the Leica TPS1200 total station. 73 scans were acquired using a Faro Focus 3D with an average target accuracy of ±4.7mm (Fig. 4). Special supports were sometimes used to hook the laser scanner onto the scaffolding. Although the terrestrial photogrammetric survey was affected by the presence of scaffolding, photographic documentation created by the Municipality immediately after the earthquake was used and processed with an accuracy of ±2.0 cm. This survey resulted in orthophotos of the main elevations of the fortress. The second survey campaign focused on digitising the earthquake-damaged pathways around the fortress for representation of accessibility, using a handheld Mobile Mapping System, GeoSLAM ZEB-HORIZON, and taking 360° pictures for a photogrammetric mesh.

4. Information sharing and accessibility

The aim of representing the state of conservation of the Stronghold, from two-dimensional drawings to three-dimensional models, was to achieve different objectives and goals, all focused on sharing the collected data. To achieve this, 3D models were created, using both HBIM and Non-uniform rational B-splines

Fig. 4: The main 3D survey operations and laser scanning data of the Stronghold of Arquata del Tronto after the 2016 earthquake.

(NURBS) elements (Piegl, 1996) with the aim of ensuring different levels of sharing. The first type of 3D model (HBIM) was developed specifically for the professionals involved in the restoration project, while the second was designed to allow for a more playful discovery of the Stronghold's history.

4.1 *Representing the Stronghold*

An early depiction of the Stronghold can be found in a 15th-century ex-voto fresco within the Sanctuary of the Icona Passatora church in Amatrice, dating back to the late 15th century (after 1480) (Fig. 5). The fresco depicts a prisoner kneeling before Saint Leonard and Virgin Mary, with the fortress visible in the background on a hill. The donjon and the circular bastion, prominent stronghold features, are portrayed.

Fig. 5: Ex-voto on the lower side of the apse in the Sanctuary of the Icona Passatora in Amatrice. In the frescoe the Virgin Mary and Saint Leonard are freeing a prisoner kept inside the Stronghold of Arquata del Tronto.

The painter's perspective on the Western facade of the Stronghold in the early depiction is uncertain. The entrance and circular bastion are shown on the right side, with the donjon positioned near the center. This deviation may be due to the limited space on the fresco. Although the main entrance to the fortress is on the eastern side, the fresco depicts the entrance on the western side, where only the cistern's entrance is visible.

It is possible that there was another entrance or the painter intended to represent the main access, even if it was not visible from their viewpoint. Despite these uncertainties, the fresco provides valuable insights into the Stronghold's early history. Another notable depiction of the Stronghold is found in an early 17th-century codex featuring various fortifications (Fig. 6).

It includes a southeastern perspective view, a northeastern perspective view, and a plan of the Stronghold. Interestingly, there is a correspondence between the two perspective views and the plan. The drawing shows the Stronghold with partially preserved double walls and an internal courtyard.

The donjon is located on the eastern side, and two bastions are on the southwestern side. The letters on the drawing indicate different functions within the inner space, including residential areas. However, the inner courtyard lacks walls and appears as a single open space. The polygonal bastion with five sides matches its present appearance, but the form of the circular bastion remains uncertain.

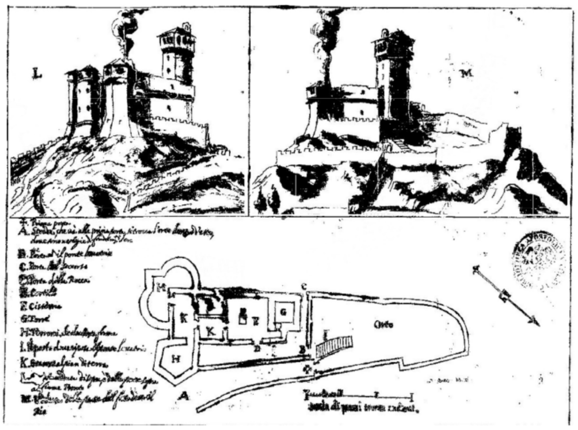

Fig. 6: Drawings of the Stronghold of Arquata del Tronto (Biblioteca Apostolica Vaticana).

The preservation of the defensive wall on the eastern side is partially incomplete, and the purpose and accuracy of the drawing's views remain uncertain (Zamperini, 2021). Moving to more recent history, two photographs capture significant events in the Stronghold during the late 19th and early 20th centuries. Towards the end of the 19th century, the Municipality of Arquata assumed ownership of the Stronghold and undertook restoration works on specific sections, although the continuity of these efforts varied. The first photograph shows the western facade of the Stronghold before the restoration, revealing collapsed sections while the circular bastion remains partially preserved (Fig. 7).

The second photo shows the Stronghold during the restoration works, specifically during the reconstruction of the merlons and donjon battlements, with scaffolding installed in the upper part of the tower (Fig. 8).

From the picture, it is possible to see what has been rebuilt during the restoration works, such as the battlements and merlons of the polygonal bastion and the western facade.

Fig. 7: Photo of the Stronghold (western facade) before the restoration works of the late 19th century/beginning 20th century (Istituto Centrale per il Catalogo e la Documentazione).

Fig.8: Photo of the Stronghold during the restoration works (estern facade), end of the 19th century/beginning of the 20th century (Istituto Centrale per il Catalogo e la Documentazione).

Collecting drawings, photos, archival documents, geometrical surveys, and on-site inspections were essential to accurately interpret and represent the Stronghold.

The correlation between drawings and geometric surveys has made it possible to approach the study of the building. Observing and interpreting the structures were even more critical. The drawings created for the research were used to report observations on the size and thickness of the walls, the texture of the walls, the arrangement of the openings, the damages after the earthquake, or the presence of structural joints (Fig. 9). The combination of orthomosaics and elevations allowed for identifying collapsed areas and mapping materials, construction techniques, and decay. Additionally, 3D models were used to understand the building and its structures in three dimensions. However, the purpose of the drawings was not solely to study the building's construction phases, but also to begin planning the restoration and project. One of the main focuses of the restoration is to improve accessibility to the Stronghold and its surroundings. To achieve this, the redesign of paths and the identification of the number, dimensions, and types of access points and their current state of conservation were crucial. In addition, green spaces and recreational areas will need to be restored and re-established throughout the site.

4.2 *3D modelling of the pathways*

The modelling of paths has been an integral part of the restoration project for analysing the state of conservation, logistics of the future construction site, and re-functionalisation of the entire area. Unlike 2D drawings, paths were created by importing the photogrammetric mesh into Rhino and drawing directly in 3D.

The resulting polylines were then imported into CAD to integrate with existing cloud-based drawings.The modelling covered a portion of Arquata's territory, including the immediate surroundings of the Rocca and a portion of the Borgo di Arquata. The terrain was modelled in Rhinoceros using contour lines extracted from the DTM file available on the Marche Region cartographic portal.

These lines were obtained from the DTM file opened in QGIS. The road system, natural elements, and buildings were then modelled, followed by integrating the paths derived from the photogrammetric survey into the general model (Fig. 10).

4.3 An HBIM for the Stronghold

The generation of the HBIM model for the Stronghold entails accurately representing its dimensions and morphology while incorporating the gathered research data. A critical aspect of this model generation process lies in ensuring the reliability of both dimensional and geometric information and the associated data on materials, construction techniques, and phases.

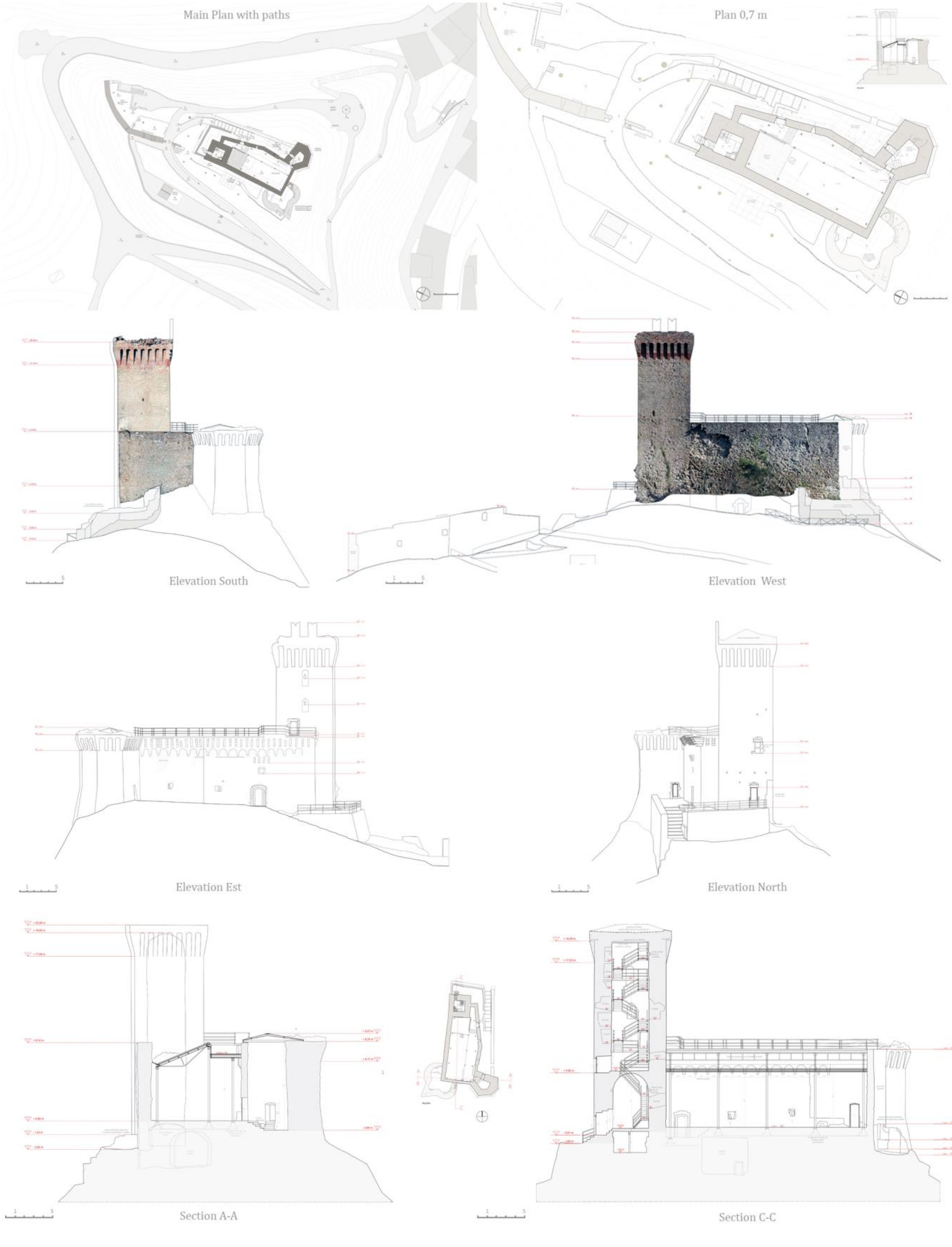

Fig. 9: The drawings of the Stronghold realised to start setting up the restoration and re-functionalisation project.

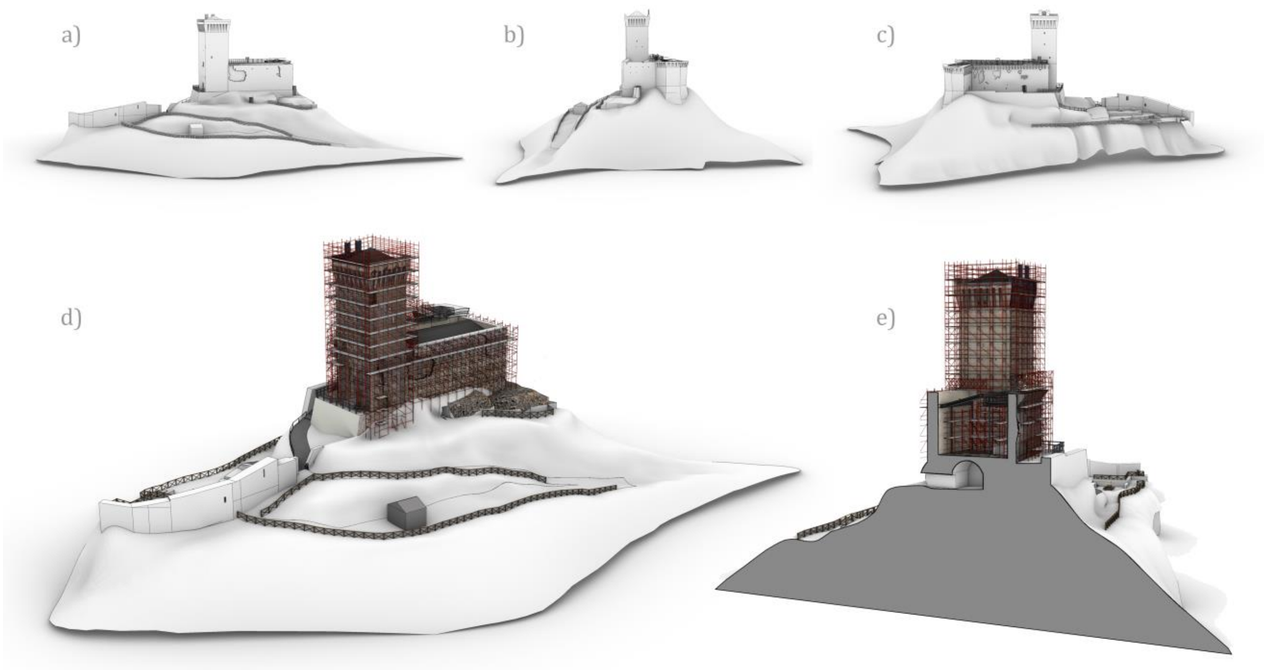

Fig. 10: The NURBS model: a) east view, b) south view, c) west view, d) NURBS texture model with UAV aerial data and scaffolding and e) 3D section model.

The exploration of increasing the Level of Information (LOI) has been extensively studied both in theory and through practical case studies.

The objective of these investigations has been to convey and recognise the value associated with ensuring the reliability of the scan-to-BIM process.

The resulting model acts as a semantic representation of the modeller's knowledge about the artefact, and digital technologies have revolutionised the way in which artefacts are semantically depicted, providing tools that facilitate the simulation of potential transformations.

Guided by their comprehensive understanding of the building to be represented, the modeller translates points in space into architectural elements within the digital environment. This intricate process involves 3D modelling and adheres to logical and practical rules that emulate the construction techniques employed during the building's original creation. A digital twin of the structure is developed by decomposing and semantically representing the building while accurately depicting its constructive logic.

During this step, the process must include discretising undetected or detectable features. This practice necessitates a geometric simplification driven by the modeller's subjective judgment.

In recent years, international guidelines and standards have aimed to prioritise geometric and informational aspects by establishing specific Levels of Detail and Information (LOD-LOI) to support the building's entire life cycle, from initial design to ongoing management during construction. However, these approaches are not always directly applicable to historical artefacts, which often possess unique and complex morphologies and typologies.

As a result, a non-standardized BIM protocol becomes necessary, where each component is clearly and precisely declared and communicated.

This differentiation ensures the geometric reliability of each element, adding value to the model and facilitating collaboration among various restoration and maintenance experts.

However, unlike new buildings, the knowledge of historical artefacts is not always complete. Even with advancements in survey techniques over the past decade, the internal consistency of construction elements may not always be accessible or representable. In such cases, the modelling team must rely on their expertise to make informed decisions and fill in the gaps,

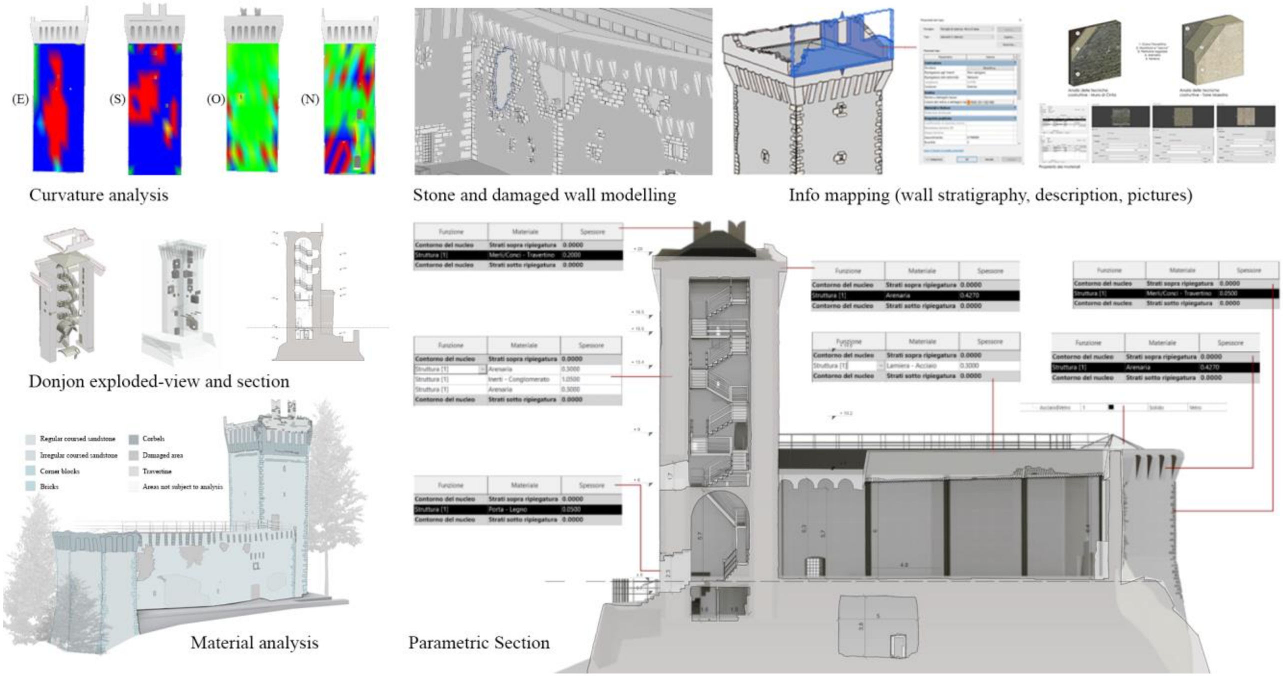

Fig. 11: The HBIM model and the association of information of different natures to expand the information value of each individual digitised component.

thereby creating a cohesive digital model that accurately represents the historical artefact.

It is a challenging process that requires a deep understanding of the building's construction techniques and materials and the ability to make informed decisions when faced with incomplete information.

The HBIM model of the Stronghold was generated using the scan-to-BIM process, and the modelling faced significant responsibilities in accurately translating the building's reality into a semantic model. Despite the challenges posed by incomplete information, the efforts were concentrated on creating a cohesive digital model (Fig. 11).

The following scan-to-BIM procedure was applied:

- Point clouds from laser scanning were imported by both the NURBS modeller and BIM platform;
- Orthomosaics from photogrammetry were used to map the model;
- The architectural elements were modelled using specific NURBS algorithms;
- The geometric reliability of each HBIM object was verified through an automatic verification system (AVS) capable of determining the standard deviation between the point cloud and the model;
- Parameters were developed for the HBIM to connect information relating to the digitisation process, such as the grade of accuracy and the sources (primary and secondary data sources), together with on-site observation and post-earthquake building assessment.
- To enhance the informational value of the HBIM model, a diverse range of information types was integrated into the model. These additions encompassed various aspects, including historical, architectural, structural, material, and functional information.
- The implementation of a database aims to establish a connection, extract, and facilitate information sharing through a shared BIM cloud logic. By utilising a database, relevant data and information from various sources can be integrated and stored in a centralised system. This allows for

efficient association and retrieval of information within the HBIM environment;
- The HBIM was oriented for different types of use, including VR.

4.4 VR Project and Virtual-visual Storytelling for the Stronghold of Arquata del Tronto

Culture involves individuals creating tangible and intangible artefacts that shape a world reflecting their cultural identity. The connection between cultural heritage and its audience is crucial, and storytelling plays a fundamental role in facilitating understanding. Narration serves as a form of recognition deeply rooted in social, cognitive, and emotional awareness, creating an interpretive framework that enhances visitors' experiences. Through narrative, individuals reassess their experiences, reconstruct meaning, and explore new perspectives, integrating intentions, motivations, ethics, and cultural values into shared cultural meanings.

In the 2000s, virtual museum experiences emerged, and in 2015, a new wave of international experimentation began. Notable examples include virtual reality exhibitions at renowned institutions like the Tate Modern, Victoria and Albert Museum, and Louvre. Museums worldwide, including the Cleveland Museum of Art, have embraced VR and augmented reality experiences. In Italy, scientific and archaeological museums utilise VR and multimedia tools to enhance visitor experiences.

Examples include the Archaeological Museum of Naples' interactive video game "Father and Son," Domus Aurea's VR and video mapping project exploring Nero's Palace, and the National Museum of Science and Technology in Milan's "Virtual Reality Zone" collaboration with Rai Cinema. These developments integrate scientific and cultural backgrounds to convey museum collection content through immersive environments (Beck, Rainoldi & Egger, 2019; Anderson et al., 2010; Hou et al., 2022).

VR is becoming increasingly integrated into our daily lives, completing the digitisation process. It creates immersive, computer-generated environments that simulate real-life experiences for users (Bekele et al., 2018). Using VR equipment, such as headsets and gloves, users can interact with the virtual environment as if it were real. VR systems track head and hand movements, enabling users to explore and manipulate objects within the environment.

In architecture, VR allows the creation of 3D models of buildings, enabling users to virtually "walk through" them before construction. VR also has immense potential for experiencing and preserving built heritage. By creating digital replicas of historic structures, VR provides immersive and interactive experiences, even for physically inaccessible or lost artefacts. VR offers a more complete and accurate representation of historic structures, allowing users to explore them from different angles and understand their design, materials, and construction techniques.

VR is also valuable for preservation purposes, aiding conservationists and historians in documenting and analysing historic structures for long-term preservation strategies. Virtual museums offer global accessibility to cultural heritage through digital technology, including websites, VR and AR platforms, mobile apps, and interactive experiences.

They enhance interactivity and customisation, enabling visitors to participate in virtual guided tours and interactive games, leading to a more engaging and involved experience. The essential functionalities of a virtual museum encompass online accessibility, virtual tools, expanded representation, digital repository, rigorous surveying and reconstruction, and customised experiences, collectively enriching visitor experiences and increasing accessibility to cultural heritage.

This study introduced innovative engagement models, transforming damaged structures into immersive cultural experiences. A narrative and process-oriented approach was employed, developing a web-VR platform that utilized functional syntax and multimedia devices to effectively convey the significance and value of Arquata's heritage. The Stronghold undertook the XR project to develop a dynamic environment accessible across multiple devices, including PCs, mobile devices, and VR headsets. Users were given the flexibility to select their preferred mode of interaction and immersion based on the capabilities of their respective devices.

Mobile devices facilitated touchscreen navigation, PCs relied on keyboards and controls, while VR headsets offered an immersive on-site experience. The system could adapt to different occasions and user preferences by seamlessly transitioning between these three modes.

Advanced 3D modelling techniques, VR tools, and XR development were employed to achieve higher levels of interactivity.

These technologies enabled users to engage with interactive virtual objects (IVOs) that consisted of mesh geometry comprising vertices, edges, and polygons. IVOs took on diverse forms, including informational panels, fantasy characters, interactive guides, flip books, level changes, teleportation points, and weather-changing features. The quality of the user experience relied heavily on implementing effective modelling techniques and exchange formats that facilitated the integration of modelling and XR development processes.

Technological advancements have significantly streamlined development efforts by integrating modelling software with XR development platforms. This integration has allowed real-time synchronisation between these software types, eliminating the need to separately save and import mesh models. As a result, developers can work simultaneously and maximise the capabilities of both software types, leading to more detailed and immersive experiences in a shorter timeframe.

The Virtual-Visual Storytelling (VVS) concept is designed around information panels and video walls that progressively immerse visitors in the tangible and intangible heritage of the Stronghold, spanning from the landscape to the architecture scale. The path begins at the main entrance of the Stronghold, situated at the base of the hill upon which it proudly stands (Fig. 12).

Visitors are encouraged to explore at their own pace, either continuing along the path or pausing at the first information point. This initial stop features a panel providing a concise description of the Village, a map displaying the 8 information points along the route, and a captivating video wall introducing the fortress's history. As visitors move forward, they can choose to linger at additional information panels and video walls that enrich the storytelling experience by recounting the significant historical events that have shaped the Borgo di Arquata throughout the centuries (Fig. 13).

The path leading to the entrance of the building offers a leisurely journey, allowing visitors to fully immerse themselves in the captivating history of Arquata and its enchanting surroundings (Fig. 14).

Fig. 12: The main entrance to the Stronghold, at the foot of the hill on which it stands.

Fig. 13: The area's main entrance.

Fig. 14: The entrance of the Stronghold.

Fig. 15: The main inner space with scaffolding and informative panels.

The internal path starts from the main entrance. From here, visitors can see a portion of the defensive wall that enclosed the stronghold area. Subsequently, the path reaches the main entrance of the stronghold. Throughout the route, video walls have been placed to describe the architecture of the stronghold and the construction phases (Fig. 15).

After exploring the inner courtyard, visitors can move to the outer section of the building using successive panoramic views, which transport them to the covered passage connecting the polygonal bastion and the upper entrance of the donjon (Fig. 16). Here, the earthquake damage to the roof and walls becomes apparent. The virtual path leads to the top of the tower, providing visitors with a panoramic view of the landscape and the impressive architecture of the structure (Fig. 17).

Fig. 16: The roofed walkway.

Fig. 17: The last information point of the VVS,

Figure 18 epicts not solely stationary devices, such as personal computers (PCs) or virtual reality (VR) headsets, but also an immersive modality grounded in web-based VR. Consequently, even individuals with limited expertise can partake in navigation within the web-VR undertaking, employing the touch screen interface of their mobile devices, devoid of any specialised hardware or software. Notably, the web-VR project is embellished with collections of images, panoramas, and videos, thereby endowing viewers with an interactive and immersive encounter, enabling them to traverse uninhibitedly through the Twinmotion scenes employing a computer, tablet, or smartphone. Furthermore, users possess the capacity to fine-tune multiple viewing parameters, encompassing navigation speed, time of day, rendering mode, and travel mode (namely, walking or flying). Importantly, by uploading the project to Twinmotion Cloud, users can disseminate it by means of the automatically generated hyperlink or Quick Response (QR) code proffered within the Twinmotion Cloud Web Drive.

5. *Results and discussion*

The research case study involved using diverse digital technologies to conduct 3D modelling to create accurate and detailed representations of a historical edifice and its environs. Laser scanning, digital photogrammetry, and HBIM techniques were implemented to capture precise measurements and intricate details, resulting in highly refined 3D models. These models proved invaluable to restoration experts as they provided a visual platform for planning and strategising restoration and preservation endeavours before their physical implementation.

Notably, HBIM models demonstrated particular advantages in facilitating research and analysis, allowing historians and restores to explore historical structures innovatively. By generating 3D models and detailed Computer-Aided Design (CAD) representations, researchers could analyse and scrutinise these structures in manners not necessarily achievable through physical access alone. This approach facilitated the discovery of novel insights and contributed to an enhanced understanding of our cultural heritage.

In creating a Virtual Reality (VR) experience, adherence to certain principles was imperative to ensure the audience's engagement's safety, enjoyment, and effectiveness. VR can induce intense and immersive experiences, potentially leading to motion sickness or nausea, especially during virtual navigation. Consequently, prioritising the physical well-being of the audience was of paramount importance. Furthermore, designing a user-friendly and intuitive experience with straightforward navigation and controls was essential to prevent confusion or frustration among viewers.

Web-VR solutions based on the Epic Games Twinmotion platform were developed to address these considerations. These solutions enable users to access and partake in interactive experiences directly through web browsers, obviating the need for additional software installations or downloads. This accessibility enables individuals with compatible browsers and VR headsets to engage with web VR experiences without necessitating extensive technical skills or additional resources. The implementation of web-VR solutions offered notable advantages. Firstly, utilising Twinmotion Cloud (Early Access) facilitated the seamless sharing of immersive and interactive presentations and panorama sets through web publication, thereby enabling the effortless dissemination of captivating content to a wide-ranging audience. Moreover, adopting a cloud-based approach effectively circumvented the complexities associated with transferring large files, effectively addressing concerns about incompatible file formats and limitations in computer performance. This streamlined process ensured the efficient and reliable delivery of virtual reality experiences.

Fig. 18: The web-VR interaction with mobile devices allows users to engage with the web-VR experience through touchscreen controls of VR headsets. Users can explore the virtual environment by utilising viewports that enable them to seamlessly teleport and navigate through the interactive content.

Users benefitted from the convenience of accessing and interacting with the content across an extensive array of devices, including workstations, laptops, tablets, and smartphones. By simply clicking on hyperlinks or scanning QR codes, users could effortlessly engage with the virtual reality content using their web browsers, thereby enhancing the accessibility and user-friendliness of the platform.

The seamless integration of presentations and panorama sets into websites using HTML embed codes from the Twinmotion Cloud Web Drive facilitated the smooth incorporation of virtual reality experiences into existing platforms. This integration resulted in enhanced user engagement and facilitated the widespread dissemination of content.

To ensure consistent visual fidelity and optimal performance, presentations uploaded to Twinmotion Cloud were hosted on cloud Graphics Processing Unit (GPU) instances. Leveraging pixel streaming technology, users were fully immersed in the virtual reality experience, allowing them to interact with scenes in a manner reminiscent of the Twinmotion environment. Consequently, this heightened the overall quality and realism of the virtual experience.

Twinmotion Cloud Early Access demonstrated compatibility with various web browsers and operating systems, encompassing Google Chrome (Android, iOS, MacOS, Windows), Apple Safari (iOS, MacOS, Windows), Firefox: Android (iOS, MacOS, Windows), and Microsoft Edge based on Chromium (Windows). This extensive compatibility ensured that users could access web VR experiences irrespective of their preferred platform, thereby maximising accessibility and broadening the reach of the content.

By capitalising on these inherent advantages, web VR solutions provided a versatile and user-friendly avenue for delivering immersive and interactive experiences, effectively tapping into the significant potential for engaging diverse audiences and facilitating a widespread exploration of virtual environments.

6. *Conclusion and future developments*

Digital architectural representation is rapidly advancing with the emergence of technologies such as 3D modelling, virtual reality (VR), and web-based VR experiences. These innovations have found diverse applications in fields ranging from gaming and entertainment to cultural heritage, museums, and education. Within this context, one promising application is the preservation and documentation of historical buildings and sites, providing valuable opportunities for documenting and studying built heritage.

In the specific case of the VR project for the stronghold of Arquata del Tronto, advanced techniques such as 3D surveying data, Non-Uniform Rational B-Spline (NURBS) modelling, and an extensive Historic Building Information Modeling (HBIM) project were employed. Drawing, 3D modelling, and extended reality have emerged as highly effective means of communication, enabling us to capture the multifaceted nature of the built environment and gain profound insights into the tangible and intangible values associated with the Rocca di Arquata del Tronto.

Significantly, drawing and 3D modeling have played a pivotal role not only as tools for graphical representation but also as spaces and moments of education and critical thinking. These activities have transcended mere manual graphic exercises and have facilitated a comprehensive exploration of the stronghold's cultural and historical significance. By utilising HBIM modelling, a thorough understanding and interpretation of the typological features of the surveyed artefacts were essential in generating accurate and informative three-dimensional representations. This involved identifying the stratigraphic units, materials utilised, and historical influences that have shaped the artefacts over time.

The demand for increased detail (Level of Detail or LOD) and information (Level of Information or LOI) in HBIM models has led to their subdivision into sub-elements capable of representing semantic structures that go beyond geometric or constructional considerations. Identifying intelligent parametric objects and establishing bidirectional relationships among them have proven indispensable in information mapping and the sharing of complex scenarios, thereby enhancing the capabilities of HBIM.

Looking towards the future, digital architectural representation holds exciting opportunities for preserving and exploring our built heritage. Ongoing technological advancements, such as deploying 5G networks, will expedite developing and deploying web-VR applications and experiences. These advancements will enable faster connections and data transfer, further advancing the utility and potential of HBIM models in digital architectural representation.

REFERENCES

Agnello, F., Cannella, M., & Geraci, M.R. (2022). AR/VR Contextualization of the Statue of Zeus from Solunto. In A. Giordano, M. Russo, & R. Spallone (Eds), *Representation Challenges: New Frontiers of AR and AI Research for Cultural Heritage and Innovative Design* (pp. 237-244). Milano: Franco Angeli. https://dx.doi.org/10.3280/oa-845-c217 .

Anderson, E. F., McLoughlin, L., Liarokapis, F., Peters, C., Petridis, P., & De Freitas, S. (2010). Developing serious games for cultural heritage: a state-of-the-art review. *Virtual reality*, *14*, 255-275.

Beck, J., Rainoldi, M., & Egger, R. (2019). *Virtual reality in tourism: a state-of-the-art review*. *Tourism Review*, *74*(3), 586-612.

Bekele, M. K., Pierdicca, R., Frontoni, E., Malinverni, E. S., & Gain, J. (2018). A survey of augmented, virtual, and mixed reality for cultural heritage. *Journal on Computing and Cultural Heritage (JOCCH), 11*(2), 1-36.

Beltramini, G., & Gaiani, M. (2017). PALLADIOlibrary–A growing virtualization project to understand Andrea Palladio's works. *SCIRES-IT - SCIentific RESearch and Information Technology*, *7*(2), 73-84. http://dx.doi.org/10.2423//i22394303v7n2p73

Bianchini, C. (2014). Survey, modelling, interpretation as multidisciplinary components of a Knowledge System. *SCIRES-IT- SCIentific RESearch and Information Technology, 4*(1), 15-24. http://dx.doi.org/10.2423/i22394303v4n1p15

Bruno, S., & De Fino, M. (2021). Decision-making for historic building diagnosis by logical inference in HBIM approach: the case of onsite inspection of timber elements. *SCIRES-IT - SCIentific RESearch and Information Technology*, *11*(2), 67-82. http://dx.doi.org/10.2423//i22394303v11n2p67

Brusaporci, S., Centofanti, M., Continenza, R., & Trizio, I. (2012). Sistemi Informativi Architettonici per la gestione, tutela e fruizione dell'edilizia storica. In *Atti 16ª Conferenza Nazionale ASITA* (pp. 315-322). Vicenza: ASITA.

Cannella, M. (2021). Hulot's Selinunte: digital analysis and virtual reconstruction. *SCIRES-IT - SCIentific RESearch and Information Technology*, *11*(2), 113-124. http://dx.doi.org/10.2423/i22394303v11n2p113

Eastman, C., Teicholz, P., Sacks, R., & Liston, K. (2011), *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors* (2). New Jersey: John Wiley & Sons Inc.

Facchi E., Grimoldi A., Landi A. G., & Zamperini E. (2021). Reconstructed overhanging battlements. Executive techniques and their vulnerability in the Stronghold of Arquata del Tronto (Italy). In P. Roca, L. Pelà, C. Molins (Eds), *Proceedings of the 12th International Conference on Structural Analysis of Historical Constructions SAHC 2020*. http://dx.doi.org/10.23967/sahc.2021.200

Ferretti, U., Quattrini, R., & D'Alessio, M. (2022). A Comprehensive HBIM to XR Framework for Museum Management and User Experience in Ducal Palace at Urbino. *Heritage, 5*(3), 1551-1571.

Galera-Rodríguez, A., Angulo-Fornos, R., & Algarín-Comino, M. (2022). Survey and 3D modelling of underground heritage spaces with complex geometry: surface optimisation for association with HBIM methodology. *SCIRES-IT - SCIentific RESearch and Information Technology*, *12*(1), 177-190. http://dx.doi.org/10.2423/i22394303v12n1p177

Gargaro, S., Del Giudice, M., & Ruffino, P. A. (2018). Towards a multi-functional HBIM model. *SCIRES-IT-SCIentific RESearch and Information Technology*, *8*(2), 49-58. http://dx.doi.org/10.2423/i22394303v8n2p49

Giordano, A., Russo, M., & Spallone, R. (2021). *Representation Challenges: Augmented Reality and Artificial Intelligence in Cultural Heritage and Innovative Design Domain*. Milano: Franco Angeli.

Grimoldi, A., Landi, A.G., & Adami, M. (2023), Past restorations and current damages in a building affected by seismic events (2016): the Stronghold of Arquata del Tronto (Italy). In *Proceedings of the SAHC-2023 Conference* (forthcoming).

Guidi, G., Russo, M., & Angheleddu, D. (2014). 3D Survey and virtual reconstruction of archaeological sites. *Digital Applications In Archaeology And Cultural Heritage*, *1*(2), 55-69.

Hou, Y., Kenderdine, S., Picca, D., Egloff, M., & Adamou, A. (2022). Digitizing intangible cultural heritage embodied: State of the art. *Journal on Computing and Cultural Heritage (JOCCH), 15*(3), 1-20.

Hussein, K. A., & Ismaeel, E. H. (2020). State-of-the-art of Historic Building Information Modelling-HBIM Trends in the Built Heritage-Review Paper. *Diyala Journal of Engineering Sciences, 13*(3), 77-90.

Ippolito, A. (2015). Digital documentation for archaeology. Case studies on Etruscan and Roman heritage. *SCIRES-IT - SCIentific RESearch and Information Technology*, *5* (2), 71-90. http://dx.doi.org/10.2423/i22394303v5n2p71

Lasorella, M., Cantatore, E., & Fatiguso, F. (2021). Smart approaches to enhance technical knowledge of in/low-accessible heritage. *SCIRES-IT - SCIentific RESearch and Information Technology, 11*(2), 97-112. http://dx.doi.org/10.2423/i22394303v11n2p97

Murphy, M., McGovern, E., & Pavia, S. (2013), Historic Building Information Modeling – Adding intelligence to laser and image-based surveys of European classical architecture. *ISPRS Journal of Photogrammetry and Remote Sensing*, *76*, 89-102.

Osello, A. (2012). *Il futuro del disegno con il BIM per ingegneri e architetti/The Future of Drawing with BIM for Engineers and Architects*. Palermo, Italy: D. Flaccovio.

Petrucci, E., Lapucci, D., & Lapucci, N. (2020). La Rocca di Arquata del Tronto: simbolo di rinascita per il territorio marchigiano colpito dal sisma. In J. Navarro Palazón, & L. J. García-Pulido (Eds.), *Defensive Architecture of the Mediterranean*, vol. 12 (pp. 1335-1342).

Piegl, L., & Tiller, W. (1996). *The NURBS book*. Springer Science & Business Media.

Rocha, G., Mateus, L., Fernández, J., & Ferreira, V. (2020). A scan-to-BIM methodology applied to heritage buildings. *Heritage, 3*(1), 47-67.

Sdegno, A., Masserano, S., Cochelli, P., Mior, D., & Gobbo, E. (2015). Augmented Painted Architectures for Communicating Cultural Heritage. *SCIRES-IT - SCIentific RESearch and Information Technology*, *5*(1), 93-100. http://dx.doi.org/10.2423/i22394303v5n1p93

Trizio, I, Savini, F., Giannangeli, A., Fiore, S., Marra, A., Fabbrocino, G., & Ruggieri, A. (2019). Versatil tools: digital survey and virtual reality for documentation, analysis and fruition of cultural heritage in seismic areas. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, *42*, 377–384.

Zamperini, E. (2021). I vulnerabili restauri del Novecento. La Rocca di Arquata del Tronto e il suo recupero. *Territorio*, 96, 48-60.