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Article

Enhancing Building Archaeology: Drawing, UAV Photogrammetry and Scan-to-BIM-to-VR Process of Ancient Roman Ruins

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Abstract: This research investigates the utilisation of the scan-to-HBIM-to-XR process and unmanned aerial vehicle (UAV) photogrammetry to improve the depiction of archaeological ruins, specifically focusing on the Claudius Anio Novus aqueduct in Tor Fiscale Park, Rome. UAV photogrammetry is vital in capturing detailed aerial imagery of the aqueduct and its surroundings. Drones with high-resolution cameras acquire precise and accurate data from multiple perspectives. Subsequently, the acquired data are processed to generate orthophotos, drawings and historic building information modelling (HBIM) of the aqueduct, contributing to the future development of a digital twin. Virtual and augmented reality (VR-AR) technology is then employed to create an immersive experience for users. By leveraging XR, individuals can virtually explore and interact with the aqueduct, providing realistic and captivating visualisation of the archaeological site. The successful application of the scan-to-HBIM-to-XR process and UAV photogrammetry demonstrates their potential to enhance the representation of building archaeology. This approach contributes to the conservation of cultural heritage, enables educational and tourism opportunities and fosters novel research avenues for the comprehension and experience of ancient structures.

Keywords: Roman aqueduct; historic building information modelling (HBIM); UAV photogrammetry; representation; building archaeology; extended reality (XR)

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1. Introduction

In addition to its international recognition for its significant role in documenting and preserving cultural heritage, building archaeology has emerged as a discipline extensively utilised by conservation architects and archaeologists in the study and practical implementation of building conservation history. Furthermore, current research in this field is focused on advancing the integration of recording methods and techniques, addressing interpretative issues such as the application of stratigraphic analysis to standing buildings, exploring the impact of theoretical paradigm shifts on the discipline and harnessing the potential of new virtual and visualisation technologies to revolutionise both methodological and interpretative approaches in the future.

In this context, integrating advanced survey techniques, including laser scanners and photogrammetry, enables the acquisition of increasingly precise point clouds and models as a foundation for building archaeology studies. Particularly for large-scale archaeological sites or structures situated at elevated locations, the use of UAV photogrammetry allows for the documentation and identification of sites that are otherwise difficult to access. Our case study is the Claudius Anio Novus aqueduct. The aqueduct, especially the portion that runs through the Tor Fiscale Park, is a discontinuous structure stratified by successive

transformations and is challenging to interpret. For this reason, building archaeology has been employed to guide analyses and elaborations.

The paper intends to offer a contribution to the ongoing research on the application of UAV photogrammetry in archaeological sites and monuments, highlighting the potential benefits of integrating drones into a comprehensive survey strategy that integrates topographic networking, laser scanning, terrestrial photogrammetry with HBIM and extended reality (XR). In recent years XR has gained renewed attention and interest in the fields of architecture and archaeology. The benefits of XR applied to built heritage are manifold in different areas, such as the documentation of historical sites and the possibility to experience immersive tours, together with the virtual reconstruction and visualisation of lost heritage and data sharing thanks to platforms that facilitate collaboration among experts involved in site analysis.

Furthermore, the 3D model has been used to realise the first approach to a digital twin (DT) of the aqueduct, which is meant to capture, store and monitor diverse information about the object of interest within a spatial and semantic database.

By employing UAV photogrammetry and a scan-to-HBIM-to-XR process, the paper shows the potential of these technologies in capturing detailed data, enabling precise documentation and supporting heritage interpretation and informed decision-making processes in archaeological and complex contexts.

2. Building Archaeology to Study Historical Buildings

2.1. Short Note about Building Archaeology in Italy

In Italy, the foundations of building archaeology, in terms of both practical and theoretical aspects, were established around 1987. During the 1990s, the discipline shifted towards various building archaeology and restoration topics, such as materials, construction techniques, building types, art history, historical interpretation and urban planning [1]. Initially, the term "building archaeology" aimed to encompass diverse experiences from multiple research centres and universities across Italy (Siena, Genova, Venezia, Brescia, Roma, Milano). However, there is still a lack of shared tools and practices in the field. Nevertheless, despite differing perspectives, building archaeology is widely recognised as a valuable tool for knowledge and an essential guide in responsible preservation projects.

The tools of building archaeology include building stratigraphy, chrono-typology, archaeometry, dendrochronology, the analysis of materials, surface finishes, construction techniques and non-destructive diagnostic investigations [2]. Building stratigraphy, borrowed from archaeology, aids in understanding the vertical sequence and interpreting the construction phases. It relies on the concept of stratigraphic units (SUs), which represent portions of a building that were likely constructed together due to a single constructive action. Therefore, knowledge of the historical construction techniques and processes specific to the building's cultural and geographical context is necessary [3,4]. However, a building's lifespan is also marked by further processes of addition (positive SUs) or removal (negative SUs) of parts to repair damages or fulfil new needs. SUs can also be categorised as surfacing units (wall masonry) or covering units (finishing). Studying unit borders and the "contact points" between different SUs becomes crucial in understanding their relationships and reconstructing the chronological sequence. Examining mortar joints is a fundamental step in the case of exposed masonry facades.

Building archaeology is a path at the boundary between two disciplines—architecture and archaeology—that complement and enrich each other. It is a multidisciplinary approach in which the archaeologist expands their observation to artefacts different from those they typically approach. At the same time, the architect borrows investigative tools from archaeology to analyse the structure they intend to restore or trace its historical evolution. Within this logic, the process of understanding a structure is a dual-lane road, where the first lane is occupied by bibliographic sources and the second by reading materials and construction techniques. Historical documentary research provides a starting point, but written documents and drawings are indirect sources, not always easy to interpret. The

"material source," on the other hand, speaks for itself directly through its forms, colours and signs of workmanship or deterioration, even if layered. However, there are limits to interpretation, even in this case [5].

For this latter aspect, the survey has served as a starting point, providing knowledge of the aqueduct's geometric, dimensional and constructive characteristics. It serves as the graphic foundation for any hypothesis' verification. The three-dimensional model has also contributed to the understanding, allowing the visualisation of the relationship between the parts of the structure and volumetric conjectures. Indirect and direct sources are complementary: their dialectical relationship enables the understanding of the complexity of the architectural object and the verification of the hypotheses formulated for various analysed aspects.

The aim of building archaeology is to understand historical phases, the succession of specific actions carried out on the structure (including the history of the construction site) and the dating of certain elements or parts of the building, and to determine the construction methods, material treatment and supply of the construction site.

To "predict the past," archaeology utilises an evidential method that, starting from visible phenomena, seeks to trace back to their causes based on deductive and inductive reasoning, from the general to the particular and vice versa. Visible phenomena can be observed in the "signs," specific characteristics of the structure through which architecture communicates its history. They provide clues and evidence for the archaeologist and should be sought in the traces of the following [6]:

- the interfaces of stratigraphic units: the boundary, the meeting point between different units, becomes essential in establishing any existing relationships between two stratigraphic units;
- mortar joints and beds of masonry: this helps to verify the constructional continuity;
- employed materials: their surface treatment, typology and characteristics provide valuable information in understanding the material culture of a specific historical phase;
- construction materials: they allow the measurement of valuable elements—for example, for mensiochronology.

Obviously, what may serve as evidence for one construction may not be applicable to another, and each aspect can be a "sign." What is currently not understood may have significance in the future, perhaps with the discovery of a new investigative system.

Especially in the field of archaeology, the outcome of an investigation is never exhaustive because it depends on many variables, such as the specific preparations of the scholar (perspective, preliminary knowledge) and the development of new methods and analysis techniques that are continually updated over time to understand certain phenomena better. Rather than providing definitive answers to the numerous existing questions, these investigations open up new research scenarios that could enrich our knowledge of such a significant monument in Rome's construction history.

2.2. Building Archaeology into HBIM in Italy: A Brief State of the Art

Research centres have developed strategies to incorporate material and decay analyses into informative platforms to align HBIM with knowledge and preservation practices. Initially, geographic information systems (GIS) were employed, providing advantages in quantitative management and data analysis compared to AutoCAD, but still limited to two-dimensional representations [7].

As BIM methods have expanded to encompass built heritage, their potential has been directed towards diverse analyses for maintenance and preservation purposes. In Italy, the Basilica of Collemaggio served as a pioneering project [8] that consolidated decades of experimental practices. Following the devastating earthquake in L'Aquila in April 2009, the basilica underwent a complex preservation endeavour involving local superintendence offices and a design support group comprising research teams from the University of L'Aquila, Sapienza University of Rome and Politecnico di Milano. ENI coordinated the

project, providing funding and technical expertise and overseeing the design and construction phases. This preservation initiative stood out by incorporating innovative technologies, such as the HBIM model, to manage various phases of preservation.

Additionally, the HBIM was utilised to generate historically significant architectural elements that were damaged during the earthquake. The model also facilitated construction site management, including formulating hypotheses regarding reconstructing the partially collapsed chevet roof and mapping materials and decay. BIM, functioning as an information system in a three-dimensional graphic space, proves to be a valuable tool for the historical-critical process of understanding built heritage.

Recently, research centres have focused on the transition from the two-dimensional to the three-dimensional visualisation of building archaeology analysis using HBIM. Some studies concentrate on field archaeological work, employing photogrammetric surveys to create 3D models of excavated stratigraphic units [9]. Archaeological stratigraphy analysis is also crucial for virtual reconstruction purposes, as explored by Demetrescu (2015) [10].

The preservation and rehabilitation plan for Castel Masegra, situated atop a rocky hillock overlooking the city of Sondrio, has been a significant undertaking since its acquisition by the Municipality in 2012 [11]. The BIM approach, in this case, aimed to represent the "volume stratigraphy" identified by dividing the model's elements based on different construction phases. Additionally, the BIM model served as a tool for the sharing of the work among the professionals involved in the project and for tourists and virtual visitors. Consequently, the study explored the potential utilisation of BIM for finite element analysis and more interactive sharing methods. Various applications were compared to leverage the model, even remotely.

In 2018, the Department of Civil Engineering at the University of L'Aquila, led by Stefano Brusaporci [12], proposed a BIM-based analysis of building archaeology for the San Vittorino complex near L'Aquila. The study focused on the wall of the old church of San Michele Arcangelo, dating back to the 4th century, to verify construction hypotheses. Two strategies were employed for the external façade: the first involved creating a parametric wall for each stratigraphic unit, comprising external facing, a core and internal facing layers. The second strategy entailed generating parametric walls for each stratigraphic unit, corresponding to the layers constituting the wall. This resulted in a parametric wall for the central core and multiple walls representing the identified stratigraphic units on the external and internal facades. Parameters such as the description, wall typology, construction phase and state of conservation were assigned to each wall. The creation of schedules in Autodesk Revit served to extract information associated with each element in tabular form. The corresponding construction phase was assigned to each stratigraphic unit, allowing for the visualisation of construction units for each historical period. In 2020, the National Research Center [13] conducted a study on the creation of an HBIM for the church of S. Francesco in Rocca Calascio, near L'Aquila. This rural building contains traces of 16th-century frescoes, and modelling of the stratigraphic units proved to be crucial. Two methods were employed: directly modelling each stratigraphic unit as a parametric family in Autodesk Revit, starting from the laser scanner-derived point cloud, and modelling the units within SketchUp and then importing them as a "mass" into Revit to transform them into parametric walls. In both cases, the parametric data for each entity were customised and updated based on the stratigraphic analysis.

Similarly, the approach of modelling directly in Revit after importing the point cloud was utilised in 2019 for the elaboration of Castello di Fossa, an ancient settlement on Monte Circolo [14]. In the same year, Diara and Rinaudo published a study on the realisation of HBIM focused on building archaeology using open-source software such as FreeCAD, which combines CAD and BIM programs. The software was implemented on multiple levels, including libraries, material databases and IFC classification [15].

These various studies represent initial attempts to incorporate building archaeology into BIM. Given the increasing interest in this field [16–18], it is crucial to establish discussion forums and develop shared tools and methods.

3. Case Study: The Claudius Anio Novus Aqueduct in Tor Fiscale Park, Rome

The Aqua Claudia is indicated by Frontinus as the eighth aqueduct of Rome, along with the Appia, the Anio Vetus, the Marcia, the Tepula, the Julia, the Virgo and the Alsietina [19]. The ninth is the Anio Novus. The Claudius Anio Novus aqueduct is therefore composed of the Aqua Claudia, on which the specus (channel) of the Anio Novus was built almost simultaneously.

The waters were collected from the upper Anio Valley, above Subiaco. The route of the two aqueducts overlaps, starting from the limaria pools, which are located at the height of the seventh mile of the Via Latina (now between Via Lucrezia Romana and Via Anagnina). After crossing Via delle Capannelle, the two channels rise first on low arches and then on increasingly higher ones, following the natural terrain and ensuring the necessary slope of the conduits. This is the most well-known stretch of the aqueduct, depicted in numerous paintings portraying the Roman countryside since the 18th century, such as the well-known engraving by Giovan Battista Piranesi. The two aqueducts run northwest towards Roma Vecchia, where the Aqua Marcia also begins its elevated path. From this point onwards, the two aqueducts run parallel to each other. After Villa delle Vignacce, they intersect twice, creating a diamond-shaped space, the so-called Campo Barbarico, near the Tor Fiscale Park, which is the focus of the research. Then, they turn north and, near Porta Furba, they follow the current Via del Mandrione until Casilina Vecchia, heading west. After passing Piazza Lodi, they reach the area of the ancient Sessorian Palace, an imperial residential complex built by Septimius Severus. The section of the Aqua Claudia adjacent to the Palace was incorporated by Aurelian into the construction of the walls, including those sections that crossed Via Labicana and Prenestina and now form Porta Maggiore. The terminal castle of the aqueduct was located near the gate, close to the Temple of Minerva Medicea, but it was demolished during the 19th century [20].

The section of the Claudius Anio Novus aqueduct located in the Tor Fiscale Park required the construction of more visible and continuous reinforcing structures, such as double brick arches (Figure 1). These arches are the only remaining and still visible constructions. The best-preserved part of this section, situated towards the north and closer to the city, consists of two large arches composed of square stone blocks with brickwork reinforcements (section D). In 2008–2009, safety and consolidation works were carried out on this section. Additionally, in 2007–2008, partial remains of the caementa cores of nearby arches (section C) were restored. The longest stretch of the aqueduct includes thirteen spans, which are defined alternately by double-arch load-bearing structures and the remaining caementa core (section G).

The *opus latericium* masonry from the Hadrianic era is well preserved for approximately three double arches. This section shows that peperino and tuff blocks were removed from the pillars and repurposed, as their imprints can still be seen on the *caementa.* Over time, the structures have been significantly altered and weakened due to spoliation, leading to prolonged exposure. Furthermore, from a structural standpoint, only the original consolidation structures of the monument are still functional. The most recent restoration of this section took place in 1964, as a plaque affixed to the structure shows.

In addition to the mentioned thirteen arches, there are other smaller monumental sections, including two peperino arches to the north (section B), which are now privately owned and were not restored in the 2000s. There are also two subsequent double arches (sections A1 and A2), with the latter located within private property. Three isolated *caementa* pillars (sections E, F, H) are separate from the rest of the structure. Only two of these pillars have undergone limited interventions (sections F, H), while section E has never been restored.



Figure 1. Detail of the Tor Fiscale Park plan and the sections of the Claudius Anio Novo aqueduct.

This section of the aqueduct is significant as it highlights the interaction between human construction and the geomorphological characteristics of the environment. These interactions have necessitated rapid structural interventions. The thickening of the piers or brickwork walls around the aqueduct (section D) during the Late Antique period indicates that the early Hadrianic interventions did not resolve the structural issues. On the other hand, the minimal intervention on the long stretch of the Claudius aqueduct in the Aqueduct Park suggests that restoration work was not required due to design deficiencies but rather other location-related problems. Roman architects were typically skilled at identifying the most suitable foundation soil. However, in this case, hydraulic requirements primarily influenced their choices to ensure a constant and controlled water flow.

The *opus quadratum* masonry of the Claudius aqueduct can be observed in section B, where a pillar and part of an arch have been preserved. It is also prominent in section D, particularly on the west side, where the pillars and arches remain (Figure 2).



Figure 2. The *Claudius aqueduct's opus quadratum* masonry identified in section D.

Another section of the original monument is located beneath the Torre Fiscale, which was built using the ancient structure as its base. In the Tor Fiscale area, the Hadrianic walls were constructed alongside each section, and, in most cases, they are the only surviving walls due to the gradual removal of the peperino blocks over the centuries. The practice of spoliation is particularly evident in section G, where the imprints of the removed stone blocks can be seen on the *caementa* walls. The Hadrianic brickwork is mostly preserved, encircling the four sides of the piers, except for the sections necessary to remove the stone blocks. The last construction phases, traditionally attributed to the Honorius period and likely dating from the Late Antique period, utilised masonry that reused Roman bricks with some courses of limestone or marble blocks.

During this phase, particularly in section D, the original pillars were dismantled and reassembled, and the opus quadratum's spoliation is noticeable (Figure 3) [21]. The peperino blocks were repositioned, sometimes reshaped to create smaller elements and placed using stone wedges and ample mortar joints. This indicates that the reshaping of the pillars no longer adhered to the ancient techniques of skilled stonemasons who could produce perfectly uniform ashlars. Specifically, on the east side of section D, the practice of spoliation deviated from the original pillar's morphology as it required strengthening and widening the base. The literature does not give much attention to the Claudius Aqueduct in the Tor Fiscale Park due to the extensive removal of the stone blocks, resulting in the near-total disappearance of the original structure. At first glance, it is challenging to identify the preserved elements of the aqueduct compared to the majestic arches in the Aqueduct Park. However, analysis through building archaeology [22] reveals extensive maintenance activities, indicating the continuous attention of Roman institutions, at least until late antiquity, towards an infrastructure considered vital for the city's functioning and the well-being of its residents.



Figure 3. The *opus quadratum's* spoliation in section D.

4. Materials and Methods

The research was based on a multi-sensor survey campaign, using a total station, laser scanner and terrestrial and aerial photogrammetry to acquire the area's dimensional, geometric and material data, including the park and aqueduct sections.

4.1. Multi-Sensor Survey Campaign

The survey activities, conducted in June and August 2021, focused on the Tor Fiscale Park area and its relation to the sectors of the Claudius aqueduct. The survey objectives included creating a plan of the entire park area with the precise positions of different aqueduct sections in a local and national cartographic reference and conducting a detailed survey of each portion of the aqueduct for the scan-to-BIM process. Overall, the survey operations aimed to accurately map the Tor Fiscale Park area, including the aqueduct sections, paths and park accesses, using geodetic techniques, UAV surveying and image processing.

The survey strategy comprised four main operations (Figure 4).

- Local geodetic network to georeference the survey in a national reference system and provide a stable reference for the combination of different survey campaigns. The network vertices were measured using a Global Navigation Satellite System (GNSS) and topographic techniques. Ground control points were used for photogrammetry and laser scanning.
- Network vertices were measured using a combination of GNSS and topographic techniques. Two different approaches were used to materialise the benchmarks for this study. The first approach, the "Order 0" benchmarks—fundamental vertexes of the network—involved placing topographic benchmarks fixed on the ground. A cast-iron covering protected these benchmarks. The second approach, the "Order I" benchmarks, utilised inox screws fixed within existing structures in the park area, such

as brick and concrete pathways and curbs. Retroreflective targets were positioned corresponding to stable points to facilitate total station repositioning. This allowed for resection strategies or repositioning on a network benchmark, using retroreflective targets to fix the azimuth angle. For the "Order 0" benchmarks (named 1000, 2000, 3000), their positions were determined using the GNSS technique through a static acquisition scheme, with each acquisition session lasting approximately 1.5 h. The measurements from these three stations were adjusted using data collected by the permanent GNSS station of the regional GNNS system located in Rome (ROUN), which served as an approximate baseline of 10 kilometres. Three independent sessions were conducted to determine the baselines: ROUN–1000 and ROUN–2000 (session 1); 1000–2000 (session 2); ROUN–3000 and 2000–3000 (session 3). The geodetic network, consisting of both "Order 0" and "Order I" benchmarks, was measured using a Leica TPS1200 total station. A least-squares adjustment was performed to compensate for discrepancies, resulting in average precision of approximately 1.5 millimetres for the benchmarks.

- A UAV survey was carried out to create a three-dimensional model of the area. The survey was conducted using the DJI Mavic Mini 2 and Mavic Mini 3 pro drones, employing two different flight altitudes. Firstly, a survey was carried out at a height of 25 m, using a double grid schema with 80% longitudinal overlap between images along the strip and 60% transversal overlap between different strips. Secondly, another survey was conducted at a height of 35 m, utilising a single grid schema with 60% longitudinal and transversal overlap. The selection of flight height was made to achieve a final orthophoto with a ground sampling distance (GSD) of 5.0 millimetres. Throughout the survey, approximately 2400 images were captured and processed into a single block. For the bundle adjustment, 10 points were utilised as ground control points (GCP), and 8 points were used as check points (CPs). The root mean square (RMS) error of the GCPs and CPs was approximately 2.0 centimetres. The DJI Mavic Mini 2 drone was used to carry out the initial photographic survey of the area, aiming to generate the overall orthophoto of the park and the three-dimensional models of the aqueduct sections. This first survey was supplemented by a second acquisition, conducted using the DJI Mavic Mini 3 pro drone, which was capable of capturing the more concealed parts of the structures, such as sub-arches, the interior sides of pillars and the water channel, thanks to the camera's ability to be oriented.

The Mini series was introduced in 2019 with the launch of the Mavic Mini, aiming to create a lightweight drone capable of delivering high-quality images and videos. The Mini 2 replaced the original model, which is no longer in production, and brought significant enhancements, especially in video quality and flight safety. The drone features a 12 Mp camera with a 1/2.3″ sensor, and, typical of this type of drone, both the focal length and aperture of the camera are fixed. The camera has a 24 mm equivalent focal length with an f2.8 aperture, and it also comes with fixed focus. Equipped with a 3-axis gimbal, the Mini 2 ensures excellent stabilisation during flights and includes bottom collision detection for added safety. However, it lacks front and rear sensors. The flight autonomy of this model is approximately 30 min under normal conditions (at a flight speed of 4.7 m/s with no wind). The DJI Mavic Mini 3 pro represents a significant advancement over its predecessor, mainly due to the integration of a larger sensor (1/1.3″) with a higher resolution (48 Mp) in the camera. While maintaining the same focal length (24 mm), the camera now boasts a brighter aperture (f1.7) and autofocus capabilities. The drone has improved obstacle detection through front and rear sensors, enhancing flight safety. Additionally, the battery life has been slightly extended to 34 min. An optional controller with its screen can be purchased, eliminating the need for a smartphone during flights. Another notable improvement compared to the previous model is the expanded controllable tilt range of the gimbal, enabling a unique portrait capture mode, which, as mentioned, helped to capture the sub-arches and other parts of the aqueduct. Regarding the camera, DJI has incorporated a Quad Bayer type filter in the sensor. This choice likely serves as a compromise to increase

the resolution while minimising noise, especially in video recording. The signal to noise ratio (SNR) influences the noise in an image, with higher values resulting in less visible noise. To improve the SNR, larger sensor cells are preferable to capture more photons and reduce signal variations between cells, thereby reducing image noise. In the Mini 3, despite the larger sensor, the resolution has been quadrupled compared to the Mini 2, leading to smaller cell sizes and potentially decreasing the SNR ratio. However, implementing a Quad Bayer filter helps to control noise when working at lower resolutions, such as 4K video and 12 Mp still photos. Pixel binning, a technique that combines information from four sensor cells for each pixel, is applied in such cases, significantly improving the SNR. This pixel binning technique is present in all analysed drones with resolutions exceeding 12 Mp. On the other hand, the maximum resolution capture mode (48 Mp) can be useful in capturing highly detailed bright scenes, but it may suffer from increased noise levels in low light conditions (Table 1).



Figure 4. Laser scanning (**upper left**) and UAV photogrammetry survey operations (**upper right**). The localisation of the benchmarks "Order 0" (1000–2000–3000) and "Order I" (in red) and retroreflective targets (blue) (**bottom**).

The purpose of the photogrammetric survey was twofold: on the one hand, to reconstruct all non-detectable areas using terrestrial laser scans (such as the upper part of the aqueduct and certain areas in the upper sections of the arches), and, on the other hand, to generate high-resolution textured models and orthophotos of the elevations, top views and sub-arches. The photogrammetric acquisitions were designed to obtain orthophotos at a scale of 1:20. Two different cameras (Canon EOS-1D Mark IV and Nikon D700) were used with varying focal lengths depending on the requirements (Table 2). Generally, a 20 mm lens was used; a 35 mm lens was used for the upper parts, while a 90 mm lens was used for

the sub-arches of the highest arches of the aqueduct (section G). Each block was acquired and processed separately. Depending on the size of the blocks, the number of processed photos ranged from 100 to 4000 images. The root mean square (RMS) of the ground control points (GCP) and check points (CP) was approximately 1.0–2.0 cm.

Table 1. Comparison of DJI Mavic Mini 2 and DJI Mavic Mini 3 pro.

		
	DJI Mini 2	**DJI Mini 3 Pro**
Focal	24 mm	24 mm
Sensor size	1/2.3″	1/1.3″
Image resolution	12 Mp	48 Mp
Aperture	f2.8	f1.7
Raw	yes	yes
Video	4 K—30 fps	4 K—60 fps
Gimbal tilt	−90° 20°	−90° 60°
Collision sensor	Bottom	Bottom Front Rear
Autonomy	32 min	34 min
Range	10 Km	7–12 Km

Table 2. Terrestrial photogrammetric survey: acquisition parameters.

	Terrestrial Camera 1	**Terrestrial Camera 2**
Camera	Canon EOS-1D Mark IV	Nikon D700
Focal	20 mm	20–35–90 mm
Sensor size	27.9 × 18.6 mm^2	35.8 × 23.8 mm^2
Image resolution	4896 × 3264 pix	4256 × 2832 pix

- A laser scanner survey of the different sections of the aqueduct was conducted using the FARO Focus 3D X 130 HDR (Table 3). The scanning acquisition was designed to ensure the maximum coverage of the aqueduct surfaces, reducing self-occlusions and ensuring an adequate point cloud density (Figure 5). Two different survey campaigns were planned, acquiring 213 scans, georeferenced with average reference precision of approximately 4 mm on the ground control points.

The two-dimensional drawings (Figure 6) were obtained using the point cloud data in Autodesk AutoCAD and McNeel Rhinoceros. For each block, three main horizontal sections were defined at an approximate elevation of 1.20 m from the ground level. These sections corresponded to the elevation of the sub-arches of the first- and second-level reinforcement structures, which varied depending on the different blocks. In some cases, they were also positioned at a higher elevation (section G). Subsequently, a cross-section was created for each block at the key points of the arches. The same section line was used to create the two internal elevations of the pillars. Finally, the top view (obtained through UAV data) and the four main elevations were created. Orthophotos obtained through UAV surveys, including the sub-arches, enriched the various outputs. Simultaneously, three-dimensional models obtained through both ground-based and aerial photogrammetry were processed using the Agisoft Metashape software (version 1.8.0). These models were used to generate the orthophotos. The photogrammetric model, consisting of a textured

mesh, was imported into McNeel Rhinoceros to carefully draw certain details, such as the outlines of the peperino stones, which were more challenging to identify in the point cloud. Additionally, other three-dimensional representations were created. A NURBS model in McNeel Rhinoceros was used to study hypotheses and reconstructions of the construction phases of the aqueduct, such as the removed peperino stone blocks of the pillars. An object-based model was created in Autodesk Revit, following the analysis of architectural archaeology. While the former is intended as a visualisation tool within an interchange software that can be used for parametric modelling (Revit) or virtual reality (Twinmotion, Unreal Engine), the latter is aimed at supporting the operational phase of knowledge and the planning of diagnostic surveys and restoration interventions. It assists operators involved in the conservation of the aqueduct.

Table 3. Faro Focus 3D X 130 HDR parameters.

	Laser Scanner
Method	Phase-based method
Error distance	Accuracy up to ±2 mm
Range	From 0.6 m up to 130 m
Noise reduction	50%
HDR	Photo overlay
HD resolution	Up to 165 Mpx colour

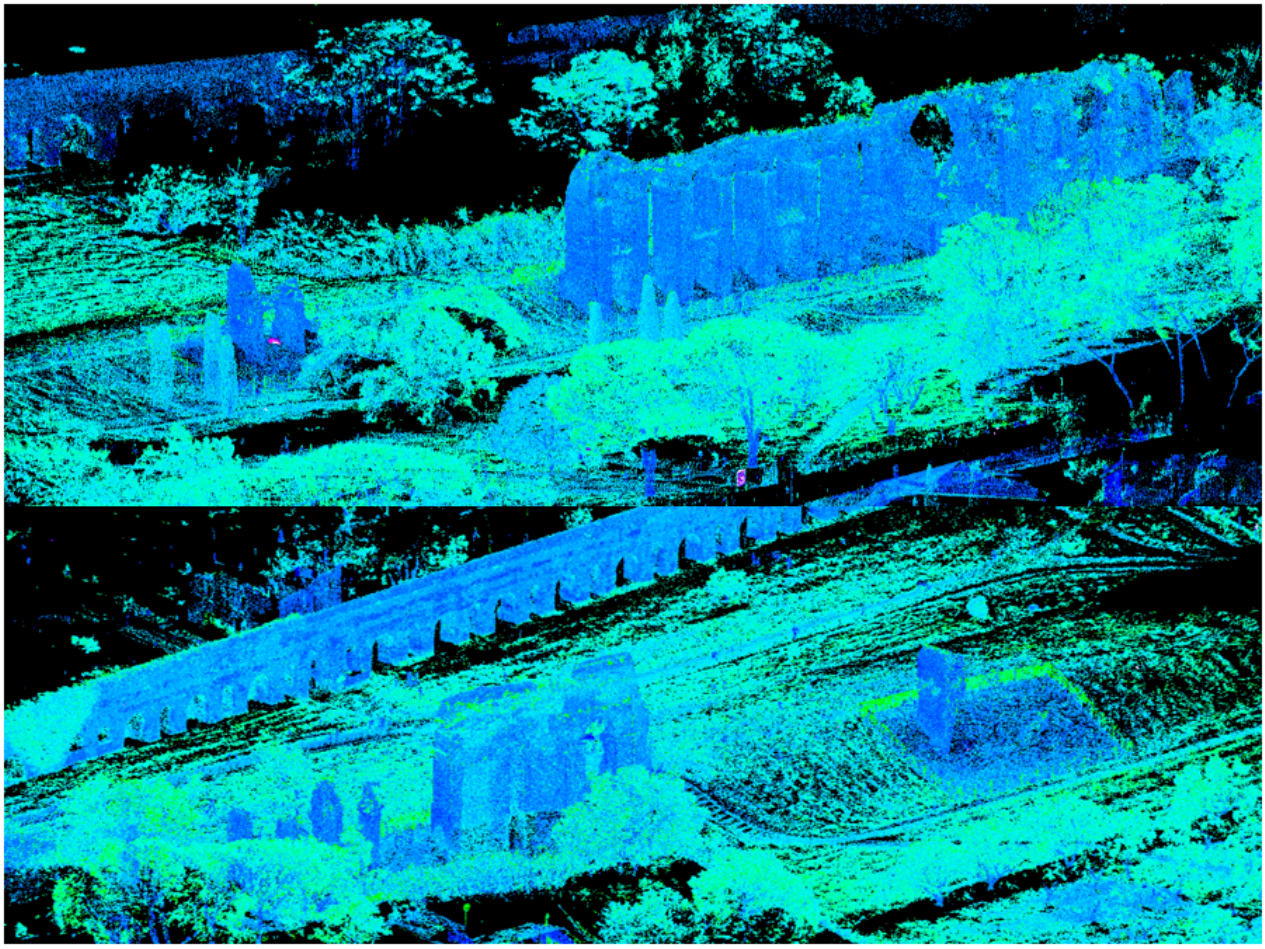

Figure 5. Laser scanner point clouds of sections G and F (**top**) and D and E (**bottom**).

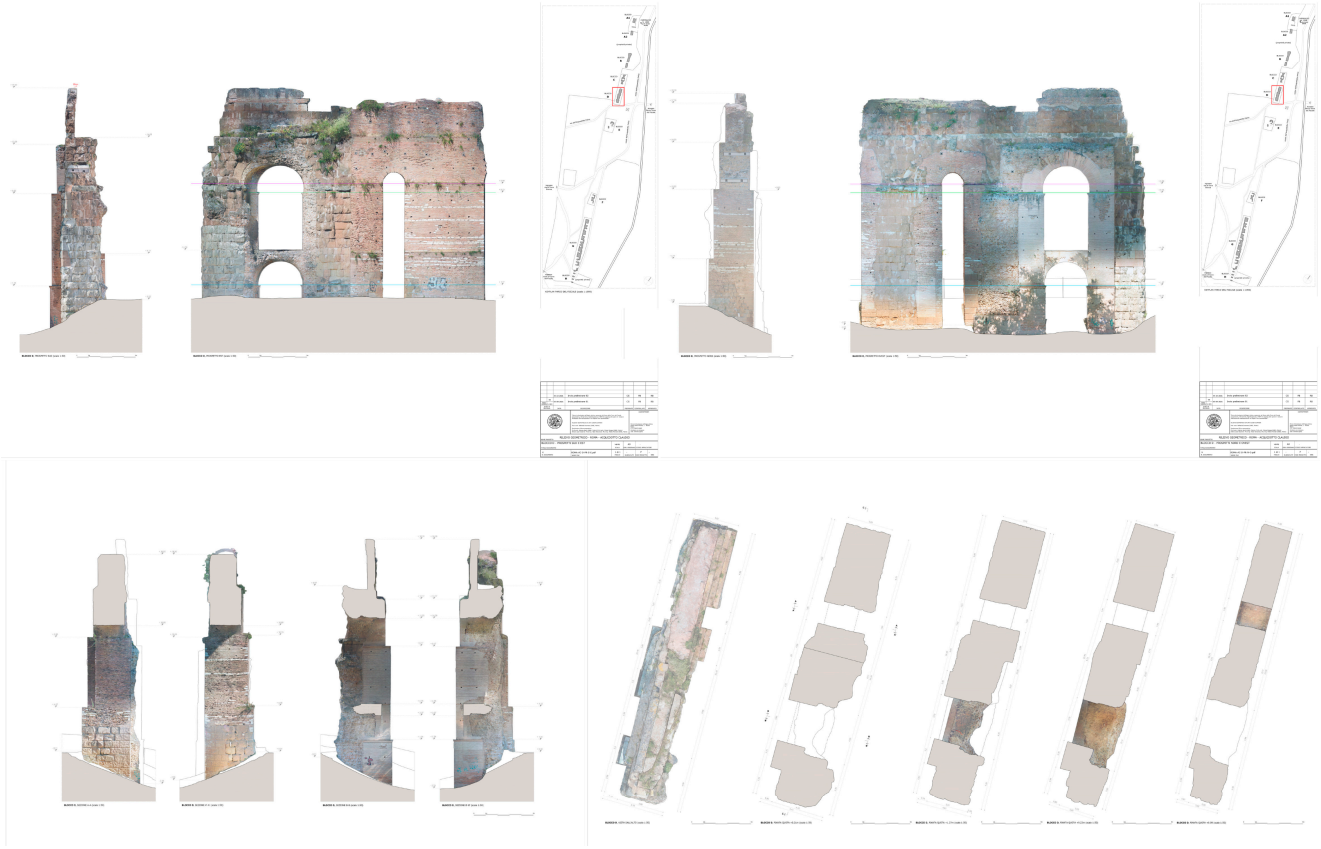

Figure 6. The drawings of section D with the dimensions: east and west elevation (**upper**); sections (**bottom left**), and plans at different levels (**bottom right**).

4.2. UAV Photogrammetry of Section D

By delving into the state of the art, various research studies have identified several benefits in digitising built heritage with aerial photogrammetry [23–28]. One of the key advantages is non-invasive data collection. Unlike traditional methods that often require physical access to heritage buildings for surveying and measurements, UAV photogrammetry allows for data collection from a distance. This approach minimises the risks associated with potential damage to delicate or fragile structures. Another benefit is high-resolution documentation [29,30]. Specifically, the drones enabled the documentation of previously inaccessible areas of the Claudius Anio Novus aqueduct, such as the upper parts of the structures and the barrel vaults between each pillar, located approximately 7 m above the ground.

UAV photogrammetry enables the capture of detailed, high-resolution images of heritage buildings from various angles and perspectives. These images serve as valuable records, documenting the current condition of the building, architectural details and historical features [31–33]. UAV photogrammetry also facilitates the comprehensive 3D modelling of heritage buildings [34,35]. Sophisticated approaches demonstrate the possibility of reconstructing buildings in three dimensions by integrating multiple overlapping images captured from different angles.

Additionally, utilising UAV thermal images and small multispectral UAV sensors further enhances the accuracy and richness of the data captured [36–38]. The 3D model enhances the understanding of the building's architecture and spatial layout. Additionally, UAV photogrammetry supports the condition assessment and monitoring of heritage buildings [39,40]. By comparing photogrammetric models created at different time points, changes or deterioration in the building's structure can be identified. These data assist heritage conservation professionals in prioritising restoration efforts and tracking the effec-

tiveness of conservation interventions. The detailed information obtained through UAV photogrammetry is invaluable for preservation and restoration planning. Architects, engineers and conservationists can analyse the 3D models to pinpoint areas needing repair, evaluate structural stability and design appropriate conservation strategies. This information contributes to preserving the historical value of the building while ensuring its long-term sustainability. Lastly, UAV photogrammetry outputs, such as high-resolution images and interactive 3D models, facilitate public engagement and education [41,42]. These resources can be shared with the public through online platforms or exhibitions, providing broader access to heritage buildings. Furthermore, they promote public involvement and education about architectural history, cultural heritage and preservation efforts.

Once the data are acquired, a vital post-processing phase is required, where many photos are processed to obtain 2D and 3D representations, which are essential for subsequent analysis stages [43–47]. During this phase, one of the key elements is the generation of orthomosaics. This involves stitching together multiple high-resolution aerial photographs to create a georeferenced image that provides a detailed and distortion-free overview of the building and its surroundings [48,49]. The orthomosaic serves as a foundation for further analysis and interpretation. Another essential component is the point cloud, which consists of a collection of 3D points accurately representing the building's surface. By extracting and correlating the 3D coordinates of distinctive features captured in multiple images, the point cloud effectively conveys the building's geometry and spatial arrangement. The point cloud data can be processed to create a 3D mesh or polygonal model to enhance the visualisation of the building's architecture. This mesh connects the points, forming triangular or polygonal facets that accurately represent the surfaces and forms of the structure. To achieve a more realistic representation of the building's appearance, the orthomosaic or 3D mesh can be textured using the original aerial imagery. The architectural representation gains visual realism by applying textures and colours to the model's surfaces, facilitating better visualisation and understanding [50–52].

Annotations and measurements also play a crucial role in highlighting specific architectural details or important elements within the representation. Labels, markers, arrows and other annotations can be added to draw attention to key features, while accurate measurements such as distances, areas and volumes can be extracted from the 3D model, supporting analysis and design processes [53–55]. Various software applications are available to visualise and render the architectural representation. These tools allow for the creation of realistic renderings, walkthroughs or virtual tours, providing an immersive experience and a deeper understanding of the building's architectural characteristics.

On the other hand, digital photogrammetry does not provide semantic models, despite the ability to generate a substantial amount of digital outputs such as orthophotos, point clouds and mesh models. Semantic enrichment provides added value and is a prerequisite in historic building information modelling (HBIM) models. As is known, HBIM models, mainly through the scan-to-BIM process, allow the professionals involved to add information. Through bidirectional and parametric logic, each BIM object can have its material type with its physical, mechanical and thermal characteristics, along with other details, such as historical phase dating, construction techniques, degradation pathologies and restoration and repair actions. In this context, understanding the artefact to be digitised and represented in various digital forms becomes the key element for the correct interpretation of each architectural and structural element [56–60]. Drawing and, more specifically, 3D modelling can be directed towards an understanding and digital transposition process in which simple points in space and textured meshes become true digital twins, capable of enhancing the awareness of the historical heritage and the tangible and intangible value of the structure itself [61,62].

All these considerations were observed in the photogrammetric survey of section D of the Claudius Anio Novus aqueduct. The photogrammetric acquisition was performed with the Canon EOS-1D Mark IV and Nikon D700. For the reconstruction of the overall shape of section D, a 20 mm lens was used. The photo-set was then integrated with a 35 mm lens,

which was used for the upper parts, and a 90 mm lens was used for the highest arches of the aqueduct. The UAV survey aimed to capture the parts not visible from the ground (top) and the arches (Figure 7). In total, 300 camera and 960 UAV pictures were acquired for a total of 1260. A set of 29 markers was used, measured with the total station. The root mean square (RMS) of the ground control points (GCP) and check points (CP) was approximately 1.0–2.0 cm. The point cloud had 6,801,707 points, while the 3D model had 5,903,747 faces and a texture of 8192 × 4096 × 40.3 bands (file size 545.34 MB).

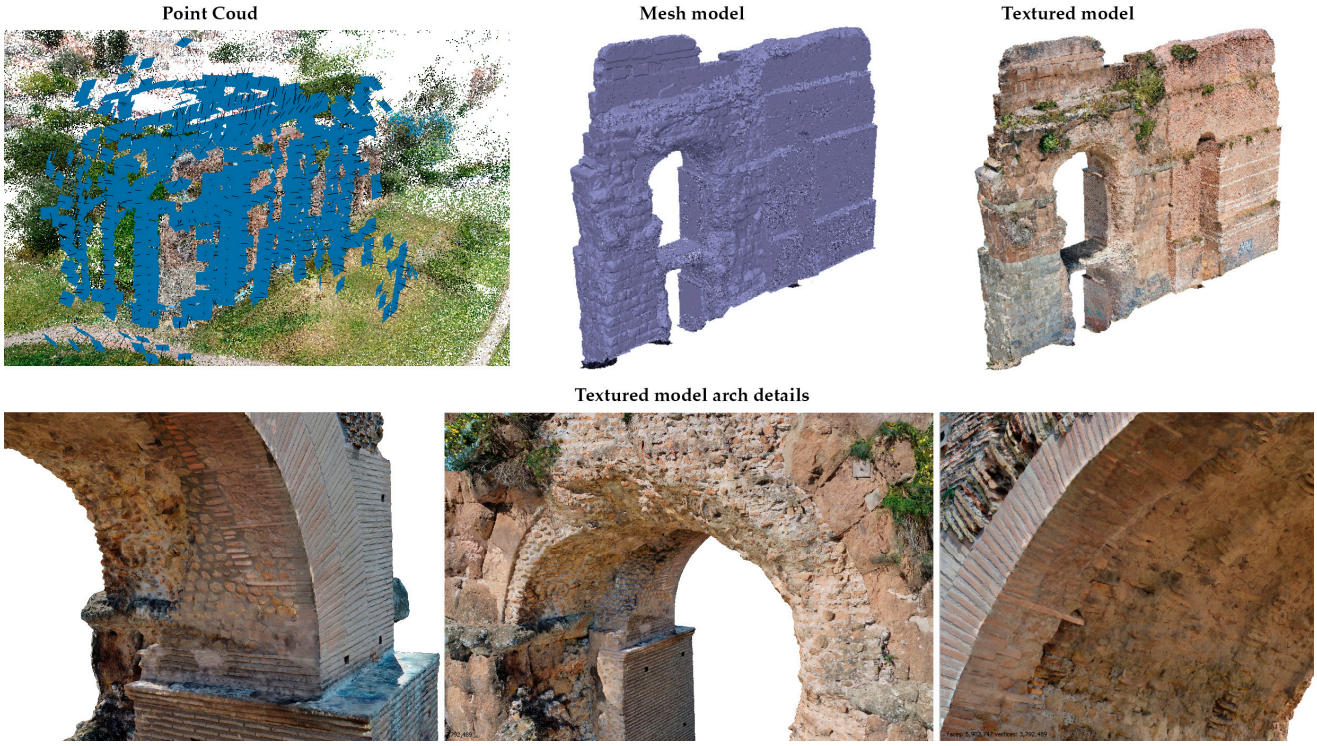

Figure 7. From point clouds to high-resolution textured models (section D).

5. Results

5.1. Studying Construction Geometries and Techniques

The detailed survey facilitated a better understanding of the construction techniques and phases of the aqueduct, as well as the analysis of material decay, which is crucial in developing a conservation design plan for the monument. Despite the stratification of the different construction phases, the structures and the heterogeneity of the materials, the Claudius Aqueduct is characterised by mostly recognisable construction phases and extensive, distinguishable recent repairs. However, these repairs are difficult to place unless otherwise documented chronologically. Each phase utilises a limited number of materials and construction techniques that are macroscopically homogeneous, usually distinguishable from those employed in preceding or succeeding phases. Specific interventions and localised repairs can also be observed (Figure 8).

The building archaeology analysis of the aqueduct, conducted at a preliminary level, is based on visual observations, bibliographic references and an initial exploration of the archives, particularly regarding 19th-century restorations. The analysis aims to identify the stratigraphic units, which correspond to areas defined by recognisable construction techniques. The analysis aims to reconstruct the history of the restorations and interventions that have affected the aqueduct structure since the early years following its inauguration in 52 AD. Each stratigraphic unit has its own record, summarising the chronological references, initial interpretations, qualitative and visual observations of the materials and possible indications for further analysis. The mapping process was carried out in two dimensions, using drawings created for geometric surveys, and in three dimensions

through the development of a dedicated HBIM for the examined sections of the aqueduct. Both masonry stratigraphic units (USM) and surface stratigraphic units (USS) have been identified (Figure 9).

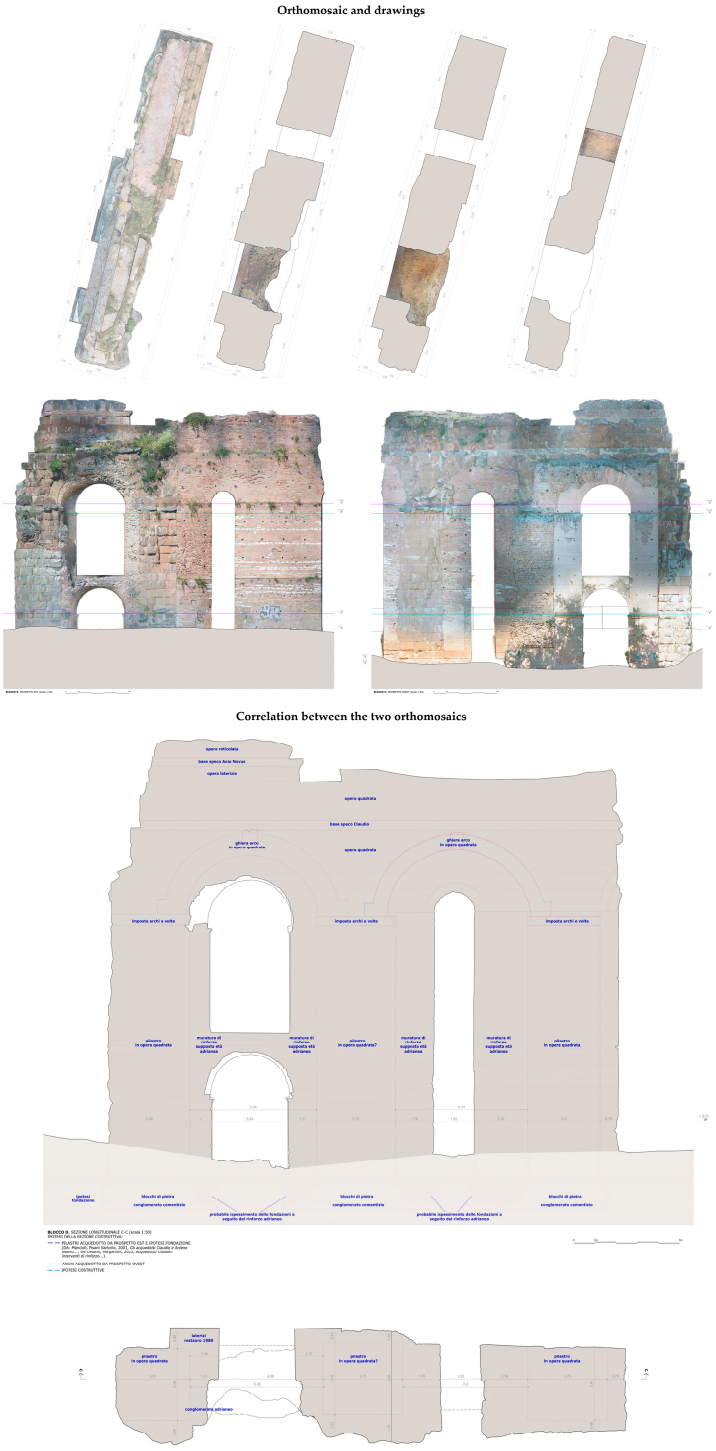

Figure 8. Hypothesis for identification of the presence of pillars and arches in peperino stone in plan and elevation, based on the correlation between the facades (orthomosaics) and the identified stratigraphic units.

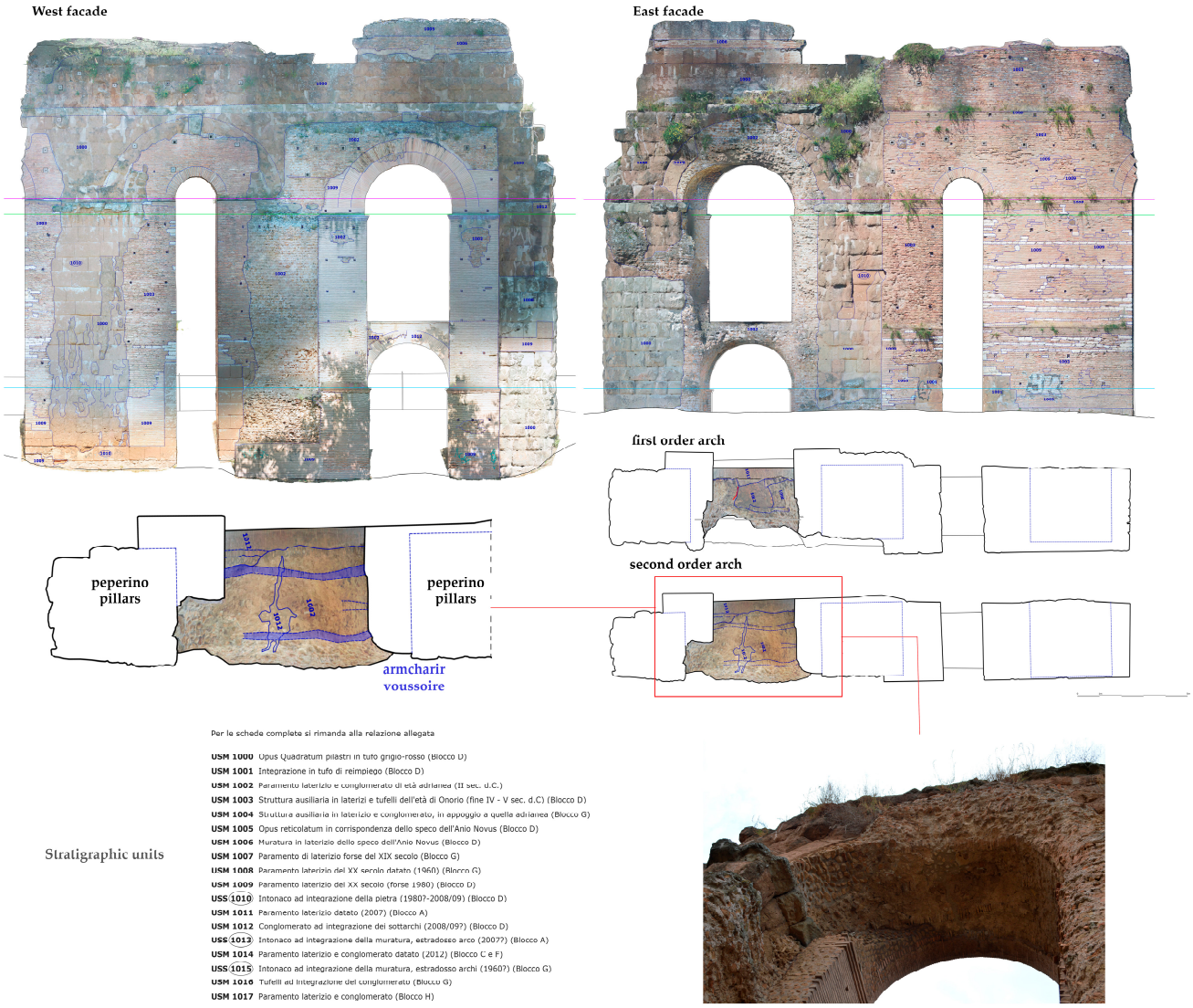

Figure 9. Building archaeology: stratigraphic units of east and west facades and sub-arches.

Section D is the only part of the aqueduct where three pillars and two arches in peperino ashlars are still partially visible. The general length of this portion of the aqueduct is approximately 24 m, with a width of 3.90 m. It consists of a stone-ashlar (peperino) pillar, measuring approximately 3.60 × 3.50 m, located to the south, and another pillar visible on the east elevation, partially incorporated into an *opus vittatum* masonry wall, which probably dates back to Onorio (395–423 d.C.) (Figure 10). A third pillar is partially visible on the west front, incorporated into the *opus vittatum* masonry wall. On both the east and west fronts, the arch in peperino can also be partially recognised. The southern pillar and the one partially incorporated into the late-antiquity wall to the north are reinforced by a double-arch structure from the Hadrianic period.

The distance between the two pillars is approximately 6.16 m. The distance between the second pillar and the third one, located to the north, has been reduced through a masonry intervention that incorporated the last pillar and narrowed the gap between them to approximately 1.80 m by constructing a much narrower arch than the Hadrianic one. The arches rest on imposts of approximately 0.45 m and are composed of a ring of peperino blocks with a trapezoidal keystone, as observed in other sections of the aqueduct, sometimes using tuff blocks. The *specus* of the Claudius aqueduct also rests on a stringcourse. Only one wall remains of the *specus*, on the west side, consisting of four courses of stone. A portion

of the *specus* of the Anio Novo aqueduct remains as an *opus reticulatum* masonry wall. The latter was likely covered by a barrel vault, as observed in the Parco degli Acquedotti and the area of the Banca d'Italia.

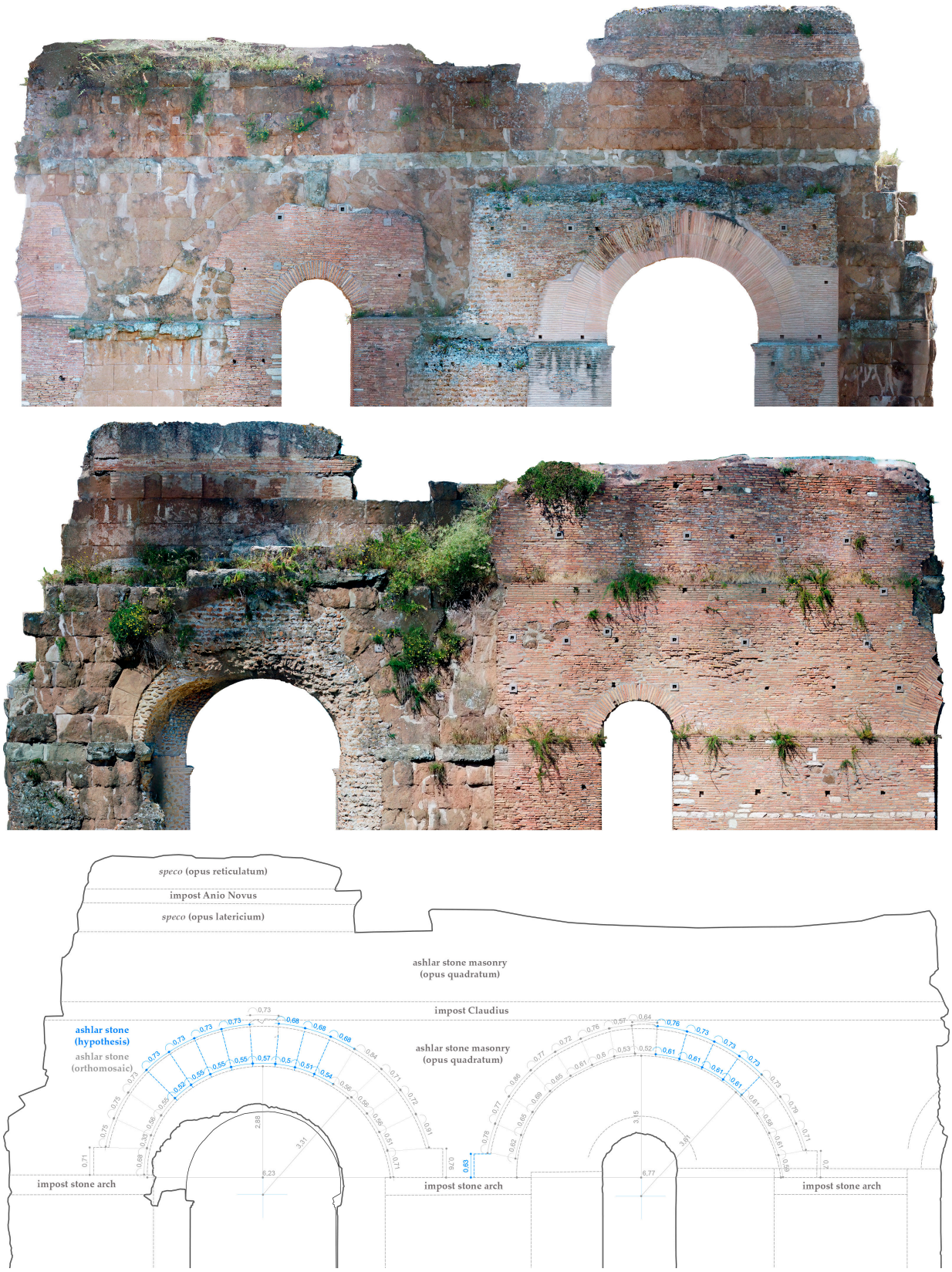

Figure 10. Arch geometries: surbased arch construction and stone dimension.

The current appearance of section D is the result of a restoration conducted in the 1980s. The brickwork was reconstructed, especially on the west side, as well as the *opus caementicium* of the Hadrianic arches, while the tuff stones were consolidated and integrated with mortars to reconstruct the shapes. In 2008, consolidation works were carried out to contain the thrust of the arches and prevent any sliding of wall sections, especially in the area related to the *specus*, and to restore the brick curtains that protected the *opus caementicium*. The additions had to be reversible and compatible with the material of the structure. A longitudinal chain was constructed, embracing the two arches, to which several transverse ties were added at the points of the putlog holes to connect the brickwork wall. It was necessary to compensate for a portion of the southern arch with lithic anchoring devices on the original masonry. Before installing the metallic ties, made of stainless steel, a cannula was inserted to allow the injection of compatible mortars. Inside the tube, the bar is housed, not injected, and therefore easily removable.

Regarding the analysis of the architectural archaeology of the sub-arches during the Hadrianic period, the construction technique of the arches is defined by bipedal brick armchair voussoirs, which also form the arch ring, and a casting of *opus caementicium*. As for the arch of the first order, it consists of two armchair voussoirs located between the two arch rings (total arch thickness: 2.48 m, span: 6.77 m). On the other hand, the arch of the second order consists of five armchair voussoirs, including the arch rings (total arch thickness: 3.70 m, span: 6.25 m). On the arch of the first order, three masonry stratigraphies have been identified: one related to the Hadrianic era (1002, *opus caementicium*) and two related to the restoration works of 1980 (1012, brickwork and *opus caementicium*). The same stratigraphies are found on the arch of the second order.

5.2. HBIM Objects for Building Archaeology Stratigraphic Units

The 3D modelling of the identified stratigraphic units was achieved through the interoperability of various software programs, including Rhinoceros, for pure modelling and parameterisation in the Revit environment [63]. This approach allowed for the accurate and comprehensive representation of the architectural elements, enhancing the site's analysis and interpretation through new information sharing forms, such as virtual and augmented reality (VR-AR).

The steps that led to the creation of the HBIM model involved four crucial moments.

- Data acquisition: laser scanner point cloud data on topographic support and photogrammetric datasets.
- Scan-to-BIM: the creation of two-dimensional drawings from the point cloud (AutoCAD), the enrichment of drawings using orthomosaics of the facades and sub-arches of aqueduct sections and the textured photogrammetric model managed in Rhinoceros. Building archaeology analysis of the elevated structure, including the mapping of stratigraphic units, analysis of alteration and degradation phenomena and creation of the HBIM model based on building archaeology.
- Information mapping: the association of information, documents, texts and images with the parametric objects of the HBIM model and the extraction of a database.
- Sharing of collected data: the transparency of information entered into the model and the possibility of integrating it with virtual or augmented reality programs.

The second point can be better explained with the following observations.

- The plans, elevations and sections of each aqueduct section were created by managing the point cloud within AutoCAD, ensuring proper georeferencing within the coordinate system defined by the topographic network with GNSS support. This ensured interoperability between different software in subsequent work phases.
- The orthomosaics obtained through data processing in Agisoft Metashape were correctly inserted and georeferenced in the CAD environment. Additionally, the CAD drawing of certain details (such as peperino blocks) benefited from the use of pho-

togrammetric models in Rhinoceros, where the three-dimensional representation provided a better understanding and allowed for the better redesign of the elements.

- Photogrammetric models and CAD drawings were georeferenced in Rhinoceros to create a NURBS model. This served two purposes: providing the basis for the parametric model in Revit and moving towards sharing formats accessible to a wider audience, such as augmented reality.
- Brick lining surfaces were parameterised in Revit within Rhinoceros. The cementitious conglomerate required more detailed modelling using the Geomagic software.
- The generated data were imported into Revit to create the parametric model. The individual stratigraphic units were defined based on the analysis of the architectural archaeology, followed by information mapping, including the definition of new parameters.

As mentioned, the modelling of complex morphologies, such as irregularly shaped walls or vaulted structures in historical architecture, including the Claudius Aqueduct conglomerate, within HBIM, using detailed surveys that generate point clouds, faces challenges in expanding the built heritage information system to high levels of detail and information. The main reason is the limited number of BIM modelling tools, which do not allow for the creation complex as-built parametric objects oriented towards built heritage. Therefore, interoperability with different programs becomes necessary to represent and create a semantic model that is as geometrically and dimensionally accurate as possible to reflect the actual state of the surveyed structure.

The challenge posed by the Claudius aqueduct is not only in terms of modelling, recognising "common" elements such as pillars, arches and imposts, which can be difficult and is perhaps less significant for the conglomerate material, but also in terms of conveying information to support the restoration project.

An HBIM supporting the project and restoration site should three-dimensionally reproduce the analyses performed on 2D drawings (or directly create them in 3D) (Figure 11). It should consider the knowledge acquired about the history, construction phases, techniques and materials through observations, diagnostic investigations, assumptions and hypotheses, in case some data have not yet been studied or made available. It should also consider the state of conservation, the mapping of alteration and degradation phenomena and any indications of previous interventions. This integration allows for a synergy between the need for knowledge and the possibilities for simulation.

The final HBIM model thus becomes a true representation not only of the object itself but of the entire construction process of the intervention. It allows for the extraction, management and control of specific aspects of interest for different professionals involved, such as material aspects and degradation. These shared aspects are collected in a single digital database that can be continuously expanded over time and gradually support research and restoration efforts.

Specifically, the implemented parameters for each modelled stratigraphic object, referring to the "Identity Data" section, include the following.

- Stratigraphic unit: This field contains the stratigraphic unit related to the parametric object (e.g., USM 1002).
- Object: Each parametric element is uniquely identified by a code consisting of the first letter corresponding to the aqueduct section (A, B, C, D, E, F, G, H), a second letter indicating the orientation of the stratigraphic unit (N = North, S = South, O = West, E = East), a number representing the stratigraphic unit (from 1000 to 1012), an additional letter indicating the type of stratigraphic unit (M = masonry, S = surface) and a progressive number to differentiate similar elements. Finally, three acronyms, 3D, TX (texture) and BIM, indicate the actual parameterisation and texturing in Revit of the object (e.g., G_O_1002_M_01_3D_TX_BIM).
- Brief description of the stratigraphic unit in Italian and English.
- Construction phase (if known or hypothesised).
- Chronological analysis (for brick linings and peperino blocks if available).

- Reference card: Link to an external repository with stored PDF-format cards for individual stratigraphic units.
- Conservation status: A brief current state description and links to reference cards.

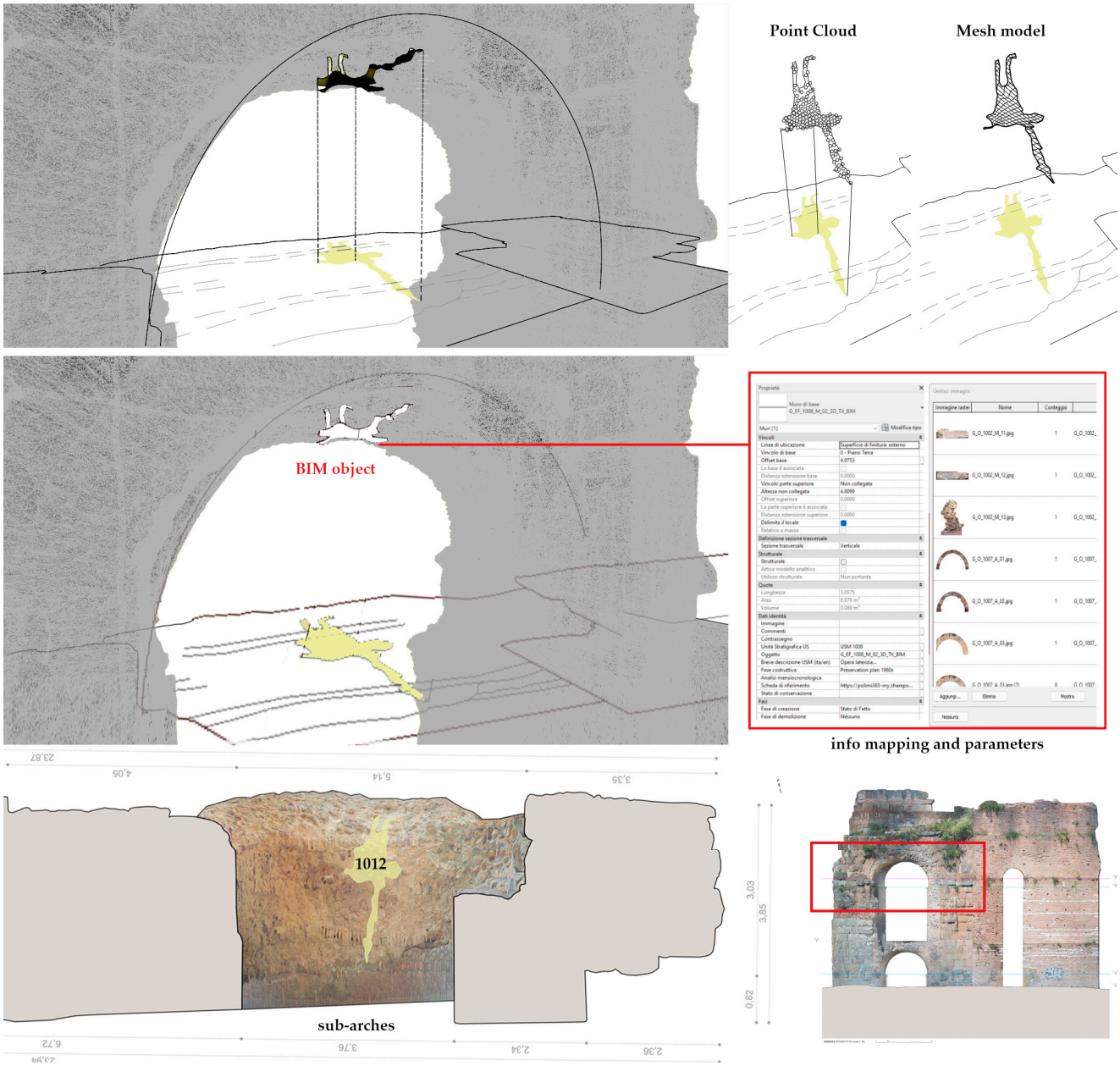

Figure 11. From NURBS to HBIM of complex shapes, such as stratigraphic units and material decay.

Additionally, in the "Image" section, orthomosaics related to each stratigraphic unit have been uploaded. This allows them to be visualised within the BIM environment and accessible as separate consultable documents. The entered data can be exported as an Excel spreadsheet, making them accessible and editable for the involved parties. At the same time, the Excel spreadsheet can serve as a basic grid for the definition of an actual database that can be subsequently linked to the BIM. This database can also consider future diagnostic investigations that need to be carried out.

The different stratigraphic units identified within the sub-arches have been modelled and imported into Revit.

5.3. From Building Archaeology and HBIM to XR

The accessibility of analysis within an HBIM project is frequently confined to a limited group of professionals actively restoring artifacts. The advent of the digital era has showcased the transformative potential of emerging technologies such as extended, virtual and augmented reality, surpassing conventional representation, visualisation and information dissemination methods [64]. In the domain of digital cultural heritage, the advancement of digital twins is still in its nascent stages. Intriguing investigations have demonstrated the feasibility of integrating real-time monitoring data with intricate models, facilitating continuous monitoring and enhancement across various stages of the lifecycle.

However, utilising and interpreting these technologies in the digital milieu necessitates advanced expertise. One must consider the intricate nature of HBIM projects and the intricate interplay between schedules, parametric objects and their associated mapped information. Concurrently, state-of-the-art VR devices necessitate a period of assimilation and adaptation for users to immerse themselves in these digital volumetric reproductions effectively [65]. Notably, the operation of VR headsets mandates specific proficiencies not universally possessed by all users.

Addressing these challenges, this study proposes a user-centric development approach centred on interpreting stratigraphic units, thereby rendering them accessible even to individuals lacking expertise in the domains of HBIM or VR.

The principal objective is to streamline the interpretation of semantic models through a novel form of shared DT facilitated via web-based platforms.

The first step to encompass a web-based platform is the development of an immersive environment wherein end-users can readily delve into the intricacies of the semantic model and its associated analyses by means as simple as a mere click on the desired area of focus. As a result, restoration specialists, archaeologists and even virtual tourists can harness this system to augment their comprehension of the artifact in an intuitive, simplified and interactive manner, with seamless interaction facilitated by touchscreen interfaces. Through targeted development leveraging visual programming languages and implementing a versatile environment accommodating both virtual and augmented reality, the understanding of the conducted analyses has been significantly enhanced on-site and remotely.

The specific development effort entailed the integration of Autodesk Revit into platforms provided by Epic Games (Twinmotion and Unreal Engine). The objective was to offer an interactive representation that was seamlessly integrated with the structural context of the Roman aqueduct while concurrently fostering enriched user interaction through a meticulously reconstructed VR environment. In particular, the VR functionality in Twinmotion supported various VR devices, including virtual reality headsets, allowing users to experience their designs with a high level of realism. By wearing a compatible VR headset, users can interact with their models using intuitive controls and movements, such as walking, teleporting and grabbing objects. This level of interactivity added a new dimension to the representation process, enabling users to test different scenarios and analyses, assess the impacts of decisions and make more informed choices. In addition to the immersive experience, the VR implementation enabled users to capture high-quality VR screenshots and videos, which could be shared with clients, stakeholders and collaborators. These visual assets provided a compelling and realistic representation of the monument, enhancing communication and understanding among all parties involved. These combined solutions facilitated comprehensive analysis directly on the HBIM model. Leveraging the potential of the semantic model, an easily navigable environment was established. Users could interact with the model by clicking on areas of interest, thereby revealing thematic zones wherein pertinent descriptions were associated. In this manner, the accessibility of these analyses surpasses conventional techniques employed for the visualisation of stratigraphic units.

Furthermore, the XR project (Figure 12) illustrates how three-dimensional morphological reproductions of construction techniques facilitate the communication of functional and formal aspects, allowing observers to interpret the detected Sus.

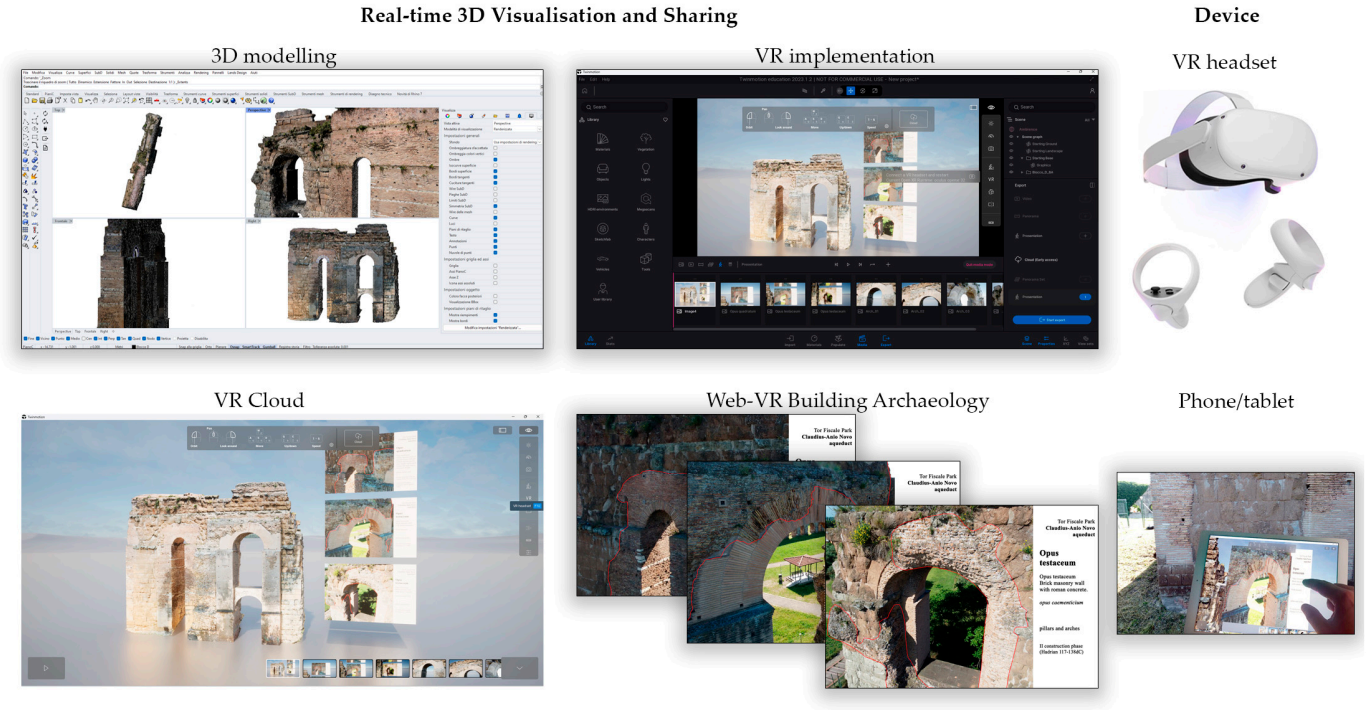

Figure 12. XR implementation for multiple devices and users.

For instance, the process of moving and installing the stone ashlars required technical expertise and construction machinery, as indicated in Plate XXIV of various Vitruvian editions of De Architectura [66].

Throughout history, from Claude Perrault's 1676 edition "Les dix livres d'Architecture de Vitruve corigés et traduits en 1648 for Claude Perrault, 1676" [67] to the 1758 edition "L'Architettura" by Marco Vitruvio Pollione," there have been dedicated chapters on Machines (Book Tenth) and Water (Book Eighth), detailing processing techniques. Table XXIV of Book Tenth illustrates the "L" iron pincer, representing the working technique called the "olive grove," used to lift large stone blocks.

By detecting segments with accuracy of 2–3 mm and representing the monument's complex morphology, the XR platform enables users to examine the three-dimensional finishes of exposed faces. Historical documentation is integrated into the HBIM gradually, including references and links to Vitruvian tables and open-access collection libraries such as Europeana.

6. Discussion and Conclusions

The possibility of integrating UAV photogrammetric surveys for the sub-arches of the Claudius Anio Novus aqueduct has allowed for a comprehensive understanding of the monument, even of the difficult-to-reach upper parts. This is important for two reasons: (i) there was no need to wait for scaffolding to study and analyse the area, and (ii) it was possible to provide preliminary support for the design of the restoration intervention. Certainly, further in-depth investigations will be necessary through observations, close inspections and diagnostic campaigns after the scaffolding is erected. Surveying with a drone has helped to overcome certain problems. The modelling that followed has benefited from the advancements of scan-to-BIM to model complex surfaces, capable of becoming BIM-enabled objects with the addition of parameters, including custom ones. Furthermore, the HBIM model was developed to serve as a foundation for a digital twin.

Building archaeology has benefited from three-dimensional representation to understand the relationships between identified stratigraphic units. Furthermore, the ability to visually represent stratigraphic units in three dimensions will assist specialists involved in restoration in making the data accessible remotely as well. In the future, for example, some of our hypotheses could be tested using instrumental investigation techniques. In fact, ongoing investigations include the analysis of mortar samples for each stratigraphic unit and soil surveys.

Web-VR has several advantages that contributed to its increased accessibility and popularity compared to traditional VR applications. One key advantage was its accessibility, as users could directly access VR experiences through web browsers, without downloading or installing dedicated applications. This eliminated the barriers associated with app installations, making VR content easily accessible to a wider audience. Incorporating textures derived from UAV photogrammetry significantly enhanced the visual fidelity and realism of the virtual environment. By carefully applying textures to the surface of the HBIM model, the colours, patterns and intricate details captured in the original aerial photographs could be faithfully reproduced. This meticulous attention to detail intensified the user's sense of immersion and active participation, creating a captivating and immersive experience.

Another notable benefit of Web-VR was its ease of sharing. Being web-based, users could effortlessly share links or URLs with others, allowing instant access to the VR content. This streamlined sharing process simplified the distribution of VR material and encouraged collaboration and shared engagement among users, facilitating a more interactive and immersive experience.

Web-VR's web-based nature also enabled real-time updates to VR content. Developers could make prompt modifications or publish new content without requiring users to perform separate updates or downloads. This ensured that users always had access to the most up-to-date version of the VR experience, fostering continuous improvement and innovation within the virtual environment.

Furthermore, Web-VR offered compatibility with a wide range of devices, including computers, smartphones, tablets and dedicated VR headsets. This cross-device platform versatility allowed users to access VR experiences through their preferred devices, without the need for specific VR hardware. This flexibility enhanced the accessibility and expanded the potential audience, creating a more inclusive VR ecosystem.

In terms of cost-effectiveness, Web-VR presented notable advantages. By eliminating the need for platform-specific or device-specific application development, the associated costs for development and maintenance were generally reduced. Additionally, users could access VR experiences without the need to invest in dedicated VR hardware, making entry into the VR world more economically viable.

Lastly, the proposed scan-to-BIM-to-XR process adds value to the development of scalable VR experiences that reach diverse audiences while effectively supporting the restoration project. Establishing a common set of tools and facilitating synchronised interventions fostered seamless collaboration among all stakeholders. The web-based infrastructure of the system enabled concurrent access by a multitude of users without any compromise in performance, thereby ensuring exceptional scalability. This aspect proved especially beneficial for immersive shared VR experiences in the research case study, including virtual tours, events and simulations, where multiple participants could interact simultaneously, fostering collaboration and facilitating shared enjoyment.

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