

# Reviving Aquileia's late antique walls: A comprehensive Extended Matrix workflow case study

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## ABSTRACT

This contribution aims to provide an overview of a virtual reconstruction case study, focusing on the late antique walls of Aquileia M2, applying the Extended Matrix methodology and its associated workflow. Specifically, we will consider virtual reconstructions in archaeological practice and address their scientific challenges. The report will address the issue of their scientific mapping, briefly touching on existing methods before delving into the details of the Extended Matrix, the chosen methodology for the project. The theoretical foundations and open-source computer tools enabling its comprehensive application will be described. Finally, the focus will be on an illustrative case study of the complete workflow: reconstructing a portion of Aquileia's defensive wall, M2. Following essential historical-archaeological contextualization, the research results leading to the reconstruction hypothesis will be presented, along with some steps to achieve the final model, its visualization through a web app, and potential future development scenarios.

**Section:** RESEARCH PAPER

**Keywords:** virtual archaeology; Aquileia; roman walls; Extended Matrix

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## 1. INTRODUCTION

Virtual reconstructions have long been integrated into archaeology, primarily serving as tools for public engagement. Despite their enduring significance in communicating and enhancing accessibility to archaeological heritage, particularly for non-expert audiences, virtual reconstructions should ideally derive primarily from rigorous scientific research.

At the forefront of recent investigations lies the imperative to transcend the pervasive “black-box effect” inherent in virtual reconstructions [1], denoting their status as closed and non-interrogable systems. This opacity obscures the demarcation between imaginative reconstructive elements and portions reconstructed upon robust scientific research or even those still preserved today. Consequently, this results in a dilution of the scientific rigor underlying the work, irrespective of the quality of the research.

The methodology known as Extended Matrix [1], [2], [3], [4], developed at CNR-ISPC, emerges as a practical approach to overcome these constraints, providing a workflow grounded in robust theoretical foundations and complemented by advanced technical tools for visualizing the outcome. The aim of this paper is to apply this three-dimensional reconstruction approach to

scrutinize a segment of Aquileia's late antique walls, elucidating the stages that define the path from archaeological research to crafting a scientifically accurate representation, to finally achieve the visualization of both virtual model and scientific mapping through a web app.

## 2. STRUCTURE OF THE PAPER

This paper develops across five main sections. Section 1 presents the introduction and the aims of this paper. Section 3 focuses on the methodologies used, describing the choice of Extended Matrix, its theoretical basis, and the tools available (Extended Matrix Framework).

Section 4 presents the case study discussed: the late antique wall of Aquileia M2. The recent investigation by the University of Verona in the city's southern section follows a brief overview of the defensive walls of Aquileia. We then focus on the comparative studies conducted to elaborate a reconstructive hypothesis.

Section 5 describes the modelling of the wall. After a short discussion about the application of the Extended Matrix, we focus on two aspects: the digital restoration of the collapsed outer face of the wall and the presence of reused materials. We

then present the final outputs via ATON and EMviq for 3D visualization.

Section 6 explores the general conclusions and outlines future scenarios.

### 3. EXTENDED MATRIX AND EXTENDED MATRIX FRAMEWORK

The exploration of reliability and uncertainty in virtual reconstructions has led to the implementation of various methodologies, all with the overarching goal of establishing a standardized process for validating models. Despite efforts to introduce clarity, a universal standard still needs to be discovered.

One dominant strategy involves adopting the "generative layers with queryable elements" paradigm, where the model is segmented based on typology and the presumed certainty associated with utilized sources, often depicted through a graduated colour scale.

Sometimes, model validation relies on "coherence gradations" derived from documentary sources, or it is organized according to "levels" and "classes" [1], [5]. Nevertheless, the reliance on source data, rather than stratigraphy, introduces a discordance between the archaeological record and the visual depiction of reliability.

Researchers have turned to quantitative methods, such as fuzzy logic, to address these challenges to compute a "Reliability Index" [1], [6]. However, the assignment of these indices relies solely on the discretionary approval of individual archaeologists, needing a direct connection to archaeological data or available sources, thus perpetuating an inherent level of subjectivity in the assessment process.

An evolving methodology for scientifically mapping archaeological reconstructions, known as the Extended Matrix, has gained prominence recently. Developed at the National Research Council - Institute of Cultural Heritage Sciences (CNR-ISPSC) laboratories, its foundational principles will be elucidated in this paragraph.

#### 3.1. Extended Matrix

The Extended Matrix [1], [2], [3], [4], [7], [8] is a formal language for scientifically mapping virtual reconstructions, uniquely tailored to accommodate archaeological investigation practices. This ensures heightened objectivity, transparency, and accessibility throughout the virtual reconstruction process. The nomenclature, "Extended Matrix," is a deliberate reference to the Harris Matrix, a fundamental tool employed in archaeological stratigraphic analysis. The Harris Matrix is a graph documenting stratigraphic and chronological relationships among Stratigraphic Units (US). Conceived as an extension of the Harris Matrix, the Extended Matrix maintains seamless continuity with established archaeological investigation practices.

The granularity of reconstructive elements adheres to stratigraphic principles, introducing Virtual Stratigraphic Units (USV) within the matrix. A Virtual Stratigraphic Unit represents a reconstructive hypothesis regarding a specific, no longer extant, stratigraphic unit.

An additional characteristic of the Extended Matrix involves the subdivision of USV. Unlike other methodologies, it refrains from basing its typology on sources, reliability indices, or the discretion of the individual scholar. As virtual stratigraphic units, they are instead categorized based on stratigraphic relationships. Two primary types of USV emerge [1]:

- Structural Virtual Stratigraphic Units (USV/S) establish a direct stratigraphic relationship with a unit that validates the "presence of absence." This may include the fracture of a partially collapsed wall, tangibly indicating its continuation, or the imprint left by a removed marble slab, offering tangible evidence of its presence despite no longer being preserved.
- Non-structural Virtual Stratigraphic Units (USV/N) principally maintain a direct relationship with other USVs, yet their stratigraphic connection and existence are uncertain, relying solely on sources.

During excavation, archaeologists frequently discover elements outside their original position during their life and use phase. These elements, play a pivotal role in virtual reconstruction but defy classification into the previously mentioned categories. In formalizing the Extended Matrix, researchers designate these elements as Special Finds (SF), virtually restoring and placing them in the hypothesized original position.

Each typology is assigned a colour code, facilitating immediate differentiation between reconstructive elements (Figure 1). In summary, the elements within the Extended Matrix include [1]:

- USM: Currently preserved stratigraphic/masonry units associated with the colour red.
- USV/S: Virtual stratigraphic units with confirmed existence through direct stratigraphic relationships associated with the colour blue.
- USV/N: Virtual stratigraphic units with existence hypothesized based on sources, not stratigraphic relationships, associated with the colour green.
- Special Find: Elements not in situ, associated with yellow. A lighter shade characterizes their anastylosis.

In graphing the Extended Matrix [2], each element (US, USV, or SF) is linked to its specific properties, known, or hypothesized, and associated with the documents used. These documents may include publications, excavation reports, surveys, photographs, etc., for existing units or the outcomes of bibliographic research, stylistic and iconographic comparisons, literary analyses, or virtual units. Due to space constraints, we cannot provide a detailed exploration of how the mapping of sources for scientific validation of hypotheses is formalized.

In conclusion, the main features of the Extended Matrix involve a commitment to archaeological granularity for the subdivision of reconstructive elements, maintaining fundamental continuity with field investigation. Furthermore, its typology is grounded not in discretionary reliability indices but in direct stratigraphic relationships and the certainty of existence, ensuring objectivity. Lastly, the mapping system for sources, though not detailed here, permits in-depth granularity within individual virtual units, where each property necessitates explicit validation, thereby guaranteeing high reliability and scientific transparency in the reconstruction process.

#### 3.2. Extended Matrix Framework

If the Extended Matrix represents a theoretical methodology applicable beyond the digital realm, the Extended Matrix Framework (EMF) constitutes a collection of digital tools and software [2], [9]. While the Extended Matrix focuses on generating scientific content, the Extended Matrix Framework offers technological solutions. The EMF currently comprises specific software add-ons (EMtools) and an investigable 3D viewer (EMviq).

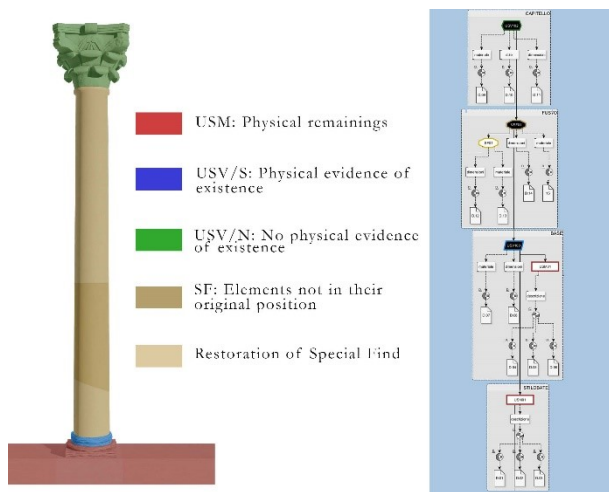


Figure 1: Example of the application of the Extended Matrix to a column. On the left is the virtual reconstruction with scientific mapping, and on the right is the graph of the extended matrix. In this instance, the stylobate and part of the base are currently preserved (in red). The missing section of the base has a confirmed existence (in blue). A shaft fragment has been discovered, not in its original position (in dark yellow), reallocated and restored (light yellow). The capital has been hypothesized based on comparisons (in green). (Nicola Delbarba).

EMtools [10], a Python-based add-on for Blender 3D, facilitates the creation of integrated 3D reconstructive hypotheses within the Extended Matrix graph. This tool enables the generation of a GraphML file in yED, a free graph creation software, including the traditional archaeological matrix. Active within Blender, it allows the association of various characteristics of Virtual Stratigraphic Units (USV) with proxies (polygons with simplified geometries corresponding to real and virtual stratigraphic units). These characteristics include era, reliability level, properties (geometry, dimensions, material, etc.), and the corresponding sources used for hypothesis validation.

EMviq (Extended Matrix Visual Inspector and Querier) [9] is a comprehensive and interactive open-source tool for real-time visualization and querying of extended matrices. It operates entirely on the web as a web app on ATON, an open-source framework developed at CNR-ISPC, previously employed in visualizing museum collections and cultural heritage assets [11]. A pivotal aspect of the Extended Matrix Framework is its open-source nature. The tools and add-ons described above are open, allowing users to modify them based on their specific needs, and they rely on free and, to the greatest extent, open-source software.

In conclusion, the Extended Matrix possesses distinctive characteristics that have led to the adoption of this methodology. Beyond those mentioned earlier, associated with its conception, objectivity, reliability, and continuity with the archaeological record, the existence of the Extended Matrix Framework facilitates the effective and complete overcoming of the initially described black-box effect. Researchers meticulously and scientifically map each reconstructed element with stratigraphic and objective coding, while an existing open-source visualization and inquiry platform plays an integral role in the workflow. This ensures a significantly higher level of transparency, usability, and accessibility than would have been possible using the Extended Matrix alone as a theoretical tool. Furthermore, the research work conducted with these tools is doubly accessible: users can engage through visualization in a web app, while researchers can exclusively utilize open-source tools and software.

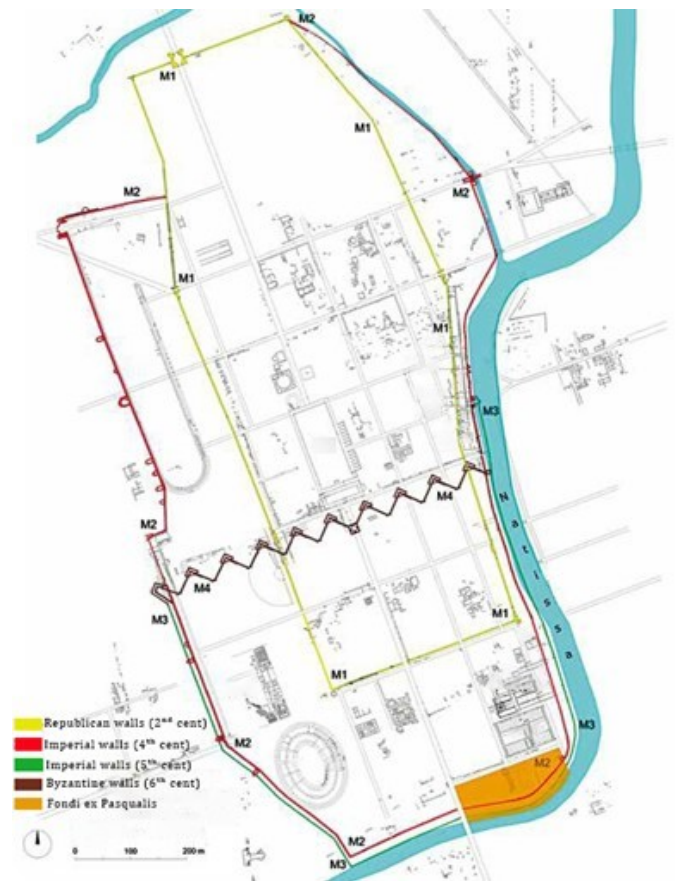


Figure 2: Aquileia plan illustrating the four defensive walls and marking the Fondo ex Pasqualis area. (Adapted from: Basso, Dobрева, Laserra 2022, p. 88, Fig. 1)

## 4. CASE STUDY: THE LATE ANTIQUE WALL OF AQUILEIA M2

### 4.1. The urban walls of Aquileia

The colony of Aquileia, established in 181 BC, is situated approximately 11 km from the Adriatic Sea and is connected to it by the *Natiso cum Turro*, flowing alongside the city's southeastern lake. Shortly after its foundation, a preliminary defensive wall, referred to as M1 in literature, was erected (Figure 2). This fortification spanned around 3000 m, outlining a north-south-oriented rectangle that enclosed an area of roughly 42 hectares [12]. In the late 1st century AD and the early 2nd century AD, the inhabitants dismantled specific sections of the walls due to a diminished defensive function [13], [14].

Herodian vividly depicts their abandoned state in a well-known passage (VIII, 2, 4-5), focusing on the 238 AD siege of Maximinus Thrax. Herodian underscores the ancient and dilapidated condition of the city's defence wall. This historical record serves as a crucial *terminus post quem* for constructing the subsequent defensive structure known as M2, which is the focal point of this research.

The construction of this new fortification nearly doubled the city's size, expanding it to over 82 hectares. Aquileia's expansion extended westward, encompassing the circus, theatre, amphitheatre, and southward along the river. This section of walls is the subject of the study and virtual reconstruction presented in this research. In the 5th century AD, an additional defensive wall, M3, was added, acting as a reinforcement along some sides of the previous structure. Lastly, in the 6th century

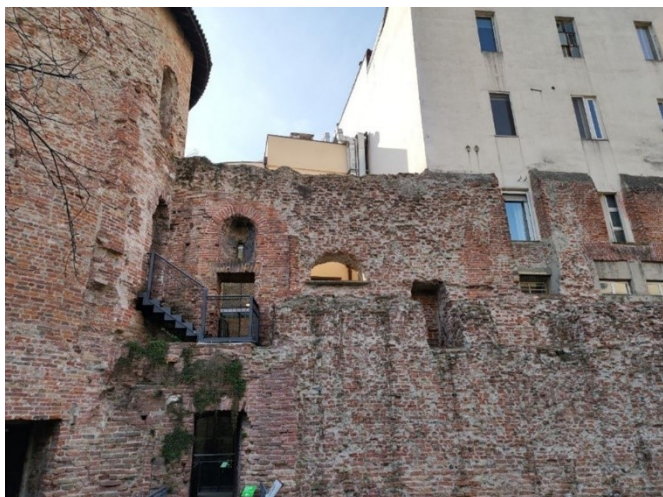


Figure 3: Segment of Massimian Walls preserved at the Archaeological Museum of Milan. Note the niche with a loophole, part of the covered walkway. (Nicola Delbarba)

AD, a new wall, M4, was erected, reducing the inhabited centre to its southern sector.

Due to spatial constraints and in line with the evolving research, this presentation will specifically focus on the late 3<sup>rd</sup> to early 4<sup>th</sup> century AD, offering an in-depth study and virtual reconstruction of the M2 defensive wall.

#### 4.2. Recent excavations by the University of Verona

The contribution centres on the Fondo ex Pasqualis, situated in the southern sector of the city (Figure 2), nestled between the Paleo Christian Basilica and the present-day Natissa River. This area holds four late antique market squares and encompasses two extensive sections of the defensive walls labelled M2 and M3. Three of these squares and the two walls were initially uncovered in the 1950s by Giovanni Brusin [15]. Ongoing excavation campaigns, led by Patrizia Basso and Diana Dobрева from the University of Verona, in collaboration with the Soprintendenza Archeologia Belle Arti e Paesaggio del Friuli Venezia-Giulia, and with the support of Fondazione Aquileia, have been underway since 2018 [16], [17], [18].

In exploring M2, recent investigations commenced with meticulously reevaluating the wall section discovered in the 1950s. The masonry, approximately 3 m wide, has been exposed for a length of around 100 m. Up to five elevation courses are preserved: the structure unveils a significant trend of material reuse, featuring architectural elements and honorary inscriptions from the 2<sup>nd</sup> century AD prominently displayed on the external façade. Subsequent research revealed that M2 was situated along the Natissa riverbank, in the city's eastern sector, during a phase when the river was more expansive, spanning about 30 m.

A particularly noteworthy revelation during the 2018 excavation campaign was a substantial section of the collapsed external façade (Figure 3). This 5.50 x 5.30 m segment presents a well-organized arrangement of 30 rows composed of bricks, pebbles, and roughly squared stones. Fragments of mortar, comprising sandy sediments with mortar clumps, are still discernible among the stones. Notably, there is a rectangular slit with a semicircular brick outline.

New investigations have also brought to light sections of the wall not yet discovered in the area and better clarified the relationship between the wall and the riverbank of the previous phase.



Figure 4: Collapsed external façade of the late antique wall "M2" found in the Fondo ex Pasqualis during the 2018 campaign. Notably, there is a rectangular loophole. (Valeria Grazioli)

#### 4.3. Comparative studies

This case study delves into late Roman defences, a subject that has garnered substantial scholarly attention over the years. Looking at the stylistic aspect, the defensive wall M2 throws up some fascinating parallels, especially in tower architecture [19], akin to the walls from the Tetrarchic period. Somewhere between 265 and 285 AD, various Italian centres, including Rome, Verona, and Milan, beefed up their fortifications in response to the brewing crisis at the Empire's northern borders [20]. Notably, the walls of Milan bear several resemblances to those found in Aquileia. Aquileia and Milan stand as the two critical pillars of Diocletian's setup in Northern Italy, underscored by similar urban planning choices between the two cities [19]. The Massimian Walls of Milan took shape between the late 3<sup>rd</sup> and early 4<sup>th</sup> centuries AD. The most pertinent section for our study is housed on the premises of the Archaeological Museum (Figure 4), featuring a tower and a wall section that is almost 20 m long and 12 m high [21]. The walls are characterised by a covered walkway sitting about 7 m above the Roman ground level. Although the upper – uncovered – walkway is now lost to time, its elevation is traceable thanks to the entrance door on the north side of the tower, hovering at a height of about 12 m.

In the tapestry of chronological, geographical, and thematic connections between cities of that era, the Milan case takes the spotlight as the most significant benchmark. Other cases have been taken into consideration for the hypothetical reconstruction of the M2 wall, particularly concerning the covered walkway, the uncovered walkway, and the battlements. In particular, we mention the Aurelian Walls of Rome, spotlighting the Aurelian frame for battlements and the Honorius phase for the covered walkway [22]. The Roman walls of Barcelona also present some traces of battlements [23].

Beyond the archaeological evidence, additional sources, such as ancient treaties as Vegetius' *Epitoma rei militari* and the Byzantine Anonymous *De re strategica*, as well as exhaustive bibliographic research and deep dives into iconographic materials as mosaics, reliefs, sarcophagi, and paintings, have all joined forces in crafting a hypothetical reconstruction. The proposed height of the wall hovers around 9 m, riding on the coattails of collapse dynamics attributed to a simple overturning [24], the strategic export of blocks from the wall's base, alongside judicious comparisons, and keen observations of siege warfare [25]. Unearthing a loophole in the collapsed façade added a compelling layer to the story, hinting at a covered walkway for sentinels, a rarity in preservation. Drawing inspiration from the

Milanese context, the envisioned scenario paints a picture of a narrow corridor blanketed by a barrel vault adorned with niches adjacent to the slits. The estimated height of the internal walkway's ground level is around 4 m above the ancient ground level.

## 5. MODELLING THE WALL

The first step in the reconstruction process was to create three-dimensional surveys of the preserved wall sections. Drone photographs (Mavic 2 Pro, DJI) were taken during the 2021 excavation campaign, capturing nadiral, frontal, and oblique angles. These images underwent processing through Agisoft Metashape software (Structure-from-Motion). The resulting models facilitated direct volumetric reconstruction based on real data, eliminating the necessity for intricate details. A low-quality setting was applied, yielding a dense point cloud comprising 6,540,273 points, a 3D model with 145,338 faces and a 2K texture. A high-definition model wasn't necessary for the set objectives, although the available tools for Extended Matrix also feature an add-on for managing various levels of quality for photogrammetric models.

The collapsed external façade of the wall was discovered in 2018. Therefore, we used a 3D model realized during that campaign by Valeria Grazioli.

Employing Blender software, the reconstruction hypothesis was modelled using as reference the obtained digital replicas. The initial model was created using simplified volumes with low-poly geometry. These geometries represent the USVs and are directly linked to the Extended Matrix, providing access to the sources used to validate the model's reconstruction hypothesis, as presented in Section 3.

Figure 5 illustrates the reconstruction *prospectus*. Starting from the bottom, there is the blocks base (USM11), with the addition of at least one missing layer (USV201), inferred from the presence of signs of removal. Above it, the stones and bricks façade are depicted (SF02), reconstructed based on the recovered

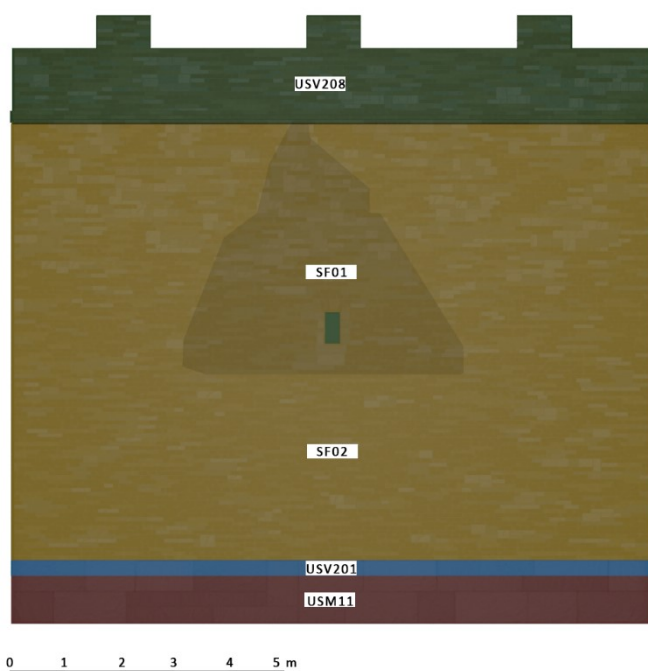


Figure 5: Reconstructive *prospectus* of M2 with US and USV (Nicola Delbarba).

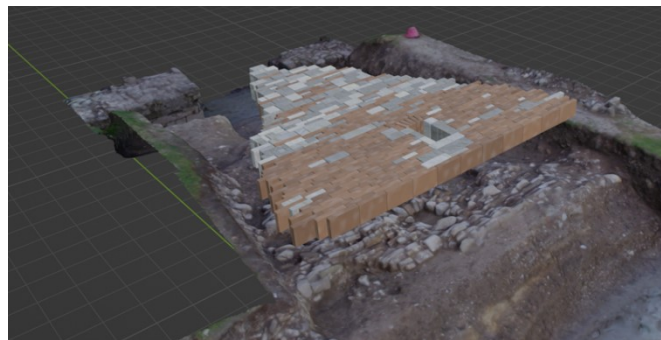


Figure 6: Blender workspace during the restoration of the wall. The work proceeded with modelling the individual elements and their respective repositioning (Nicola Delbarba).

portion of the collapsed structure (SF01). Following that, there's the crenelated parapet (USV208), its dimensions derived from the Aurelian Walls of Rome.

Subsequently, the focus shifted towards constructing a photorealistic model (Representation Model). This discussion will focus on two distinctive facets of this case study: handling the collapsed section and incorporating reused elements within the city wall.

While unearthing the collapsed façade offered precious data and insights, its virtual representation in the model was a complex challenge. Leveraging pre-existing textures to achieve a visual result faithful to the archaeological data could have been more practical, nevertheless the unique amalgamation of bricks and stones, unevenly dispersed, needed for a tailored approach. Consequently, manual modelling of individual construction elements ensued, incorporating essential corrections to accommodate inevitable shifts linked to collapse and deterioration (Figure 6). The resulting model segment then served as a launchpad for completing the remaining sections to uphold the observed frequency of bricks and stones within the collapse. To obtain a brick texture that closely resembles reality, we employed a Musgrave Texture alongside a randomized Color Ramp. This was particularly effective in expanding the colour spectrum of the elements, drawing inspiration from the yellow hues commonly found in the excavated bricks. For the stones, we utilised a free PBR texture, personalized with a randomized Color Ramp.

Although the resultant model, representative of a 10 m stretches of the wall, encompassed approximately four thousand elements – a data volume not easily manageable for exportation intended for visualization – it laid the groundwork for the baking process. This approach facilitated achieving the same scientific and aesthetic result on a geometrically less complex model, significantly reducing the polygon count from hundreds of thousands to a few dozen. This, in turn, ensured the necessary features for file export and practical accessibility.

All individual elements were subsequently merged into a single object while retaining colour randomization, achieved through the utilization of the Geometry - Random Per Island node. The facade alone encompassed roughly 650,000 vertices, excluding crenelated parapets and base blocks. A simplified volume, maintaining the same geometry, was constructed with a total of 42 vertices. The texture of the high-poly object was then baked onto the low-poly counterpart, yielding Diffuse, Normal, and Roughness maps at a resolution of 2K.

The other focal point concerned the treatment of reused elements within the lower portion of the wall. Due to their

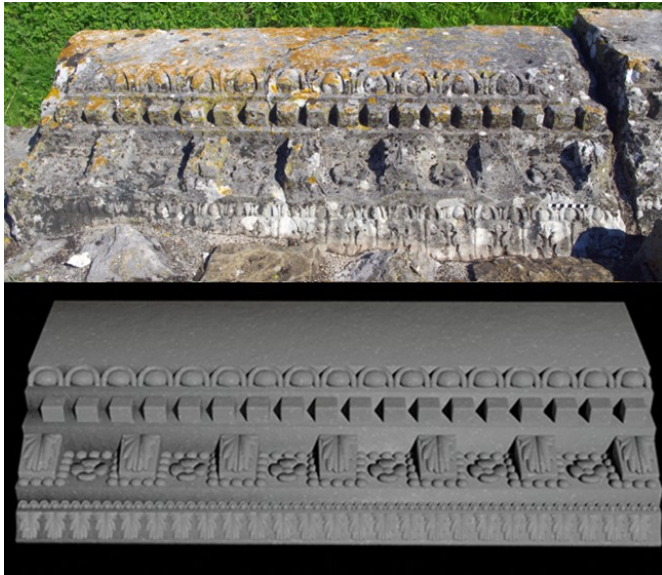


Figure 7: Left, a frame element utilised as a reused block in the construction of M2. Right, its virtual reconstruction (Nicola Delbarba)

frequency and historical, archaeological, and aesthetic significance, these elements warranted special attention. The goal was to make these elements investigable, even though they are not virtual units, allowing for their visualization within the model and providing accessibility to historical, archaeological, and stylistic information. In this case study, the virtual restoration of one of the better-preserved decorative elements – a portion of a cornice – was undertaken (Figure 7). Clicking on each element allows viewing its reconstruction and accessing a technical sheet containing relevant information. A future goal is to implement a specific treatment for reuse elements with a specific formalization within the Extended Matrix.

The work concluded with modelling the remaining elements and their exportation through ATON and EMviq.

ATON, conceived by B. Fanini (CNR ISPC), is an open-source framework built on Node.js and Three.js. It's tailored to develop Web3D/WebXR applications such as presenters, applied games, and tools, enabling interaction with Cultural Heritage (CH) objects and 3D scenes on the Web. ATON ensures seamless adaptation to various devices (mobile, desktop/kiosk, or immersive XR) without necessitating user installations.

The result accessible on ATON (Figure 8) showcases a section of the wall featuring the lower part in blocks with reused elements inside, the uncovered collapsed wall and its completion, the discovered slit, the covered passage, and the niche corresponding to the loophole. A preset tour enables guided navigation, with a particular focus on one of the reused elements used in the base.

Within the EMviq visualization (Figure 9), an experimental extension of Aton, users can query the model, thus ensuring a user-friendly and open version of the Extended Matrix. Volumes corresponding to both real and virtual stratigraphic units are displayed above the loaded representation model in ATON. Clicking on individual units allows users to access their associated metadata on the right, organized by properties. The version presented here is still in an experimental stage and requires fine-tuning and quality checks. Nonetheless, it undeniably marks a significant stride towards enhancing the accessibility of scientific research and ensuring transparency in virtual reconstruction.



Figure 8: Screenshot of ATON with the photorealistic representation of the M2 portion. The user can freely investigate the model. Representing a single portion also makes it possible to observe the internal construction techniques and the presence of the covered walkway. (Nicola Delbarba).



Figure 9: Screenshot of ATON-Emviq with the representation of USVs superimposed on the photorealistic model. Users can freely investigate the model. They can read the reasoning to validate the reconstructive hypothesis and the sources used by clicking on the individual units. In this example, the crenelated parapet is being explored (Nicola Delbarba).

## 6. CONCLUSIONS

The presented case study offers a comprehensive insight into the ongoing trajectory of a research project focused on reconstructing the entire excavation site, including the 5<sup>th</sup> century AD wall and the market squares. Nonetheless, some considerations can be made on the effectiveness of the applied methodology. The web-app visualization, notably, surpasses the predetermined transparency objectives, ensuring a thoroughly explorable and accessible reconstruction. Leveraging the inherent features of the Extended Matrix, the connection with archaeological data is robust, facilitating a scientifically meticulous, objectively reliable, and finely nuanced research granularity. The open-access ethos inherent in this methodology allows for nimble adjustments and tailor-made implementations, exemplified by the ongoing development of a customized modification to address reused elements. This adaptation, once finalized, stands to be shared and adopted by fellow members of the scientific community. Furthermore, the ultimate output

holds scholarly significance and is designed to be user-friendly for the wider public. It is a crucial educational and communicative instrument for the excavation site, ensuring that research outcomes are disseminated effectively and engagingly to academic and non-academic audiences.

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## REFERENCES

- [1] E. Demetrescu, Archaeological stratigraphy as a formal language for virtual reconstruction. Theory and practice, *Archaeological Science* 57 (2015), pp. 42-55.  
DOI: [10.1016/j.jas.2015.02.004](https://doi.org/10.1016/j.jas.2015.02.004)
- [2] E. Demetrescu, B. Fanini, A white-box framework to oversee archaeological virtual reconstructions in space and time: Methods and tools, *J. Archaeol. Sci. Rep.* 14 (2017), pp. 500–514.  
DOI: [10.1016/j.jasrep.2017.06.034](https://doi.org/10.1016/j.jasrep.2017.06.034)
- [3] E. Demetrescu, Virtual reconstruction as a scientific tool: the Extended Matrix and source-based modelling approach, in: *Digital Research and Education in Architectural Heritage*. S. Münster, K. Friedrichs, F. Niebling, A. Seidel-Grzesińska (editors). Springer, Cham, Dresda 2018, pp. 102-116.  
DOI: [10.1007/978-3-319-76992-9\\_7](https://doi.org/10.1007/978-3-319-76992-9_7)
- [4] E. Demetrescu, D. Ferdani, From field archaeology to virtual reconstruction: a five steps method using the Extended Matrix, *Appl. Sci.* 11 (2021), pp. 359-377.  
DOI: [10.3390/app11115206](https://doi.org/10.3390/app11115206)
- [5] I. Cáceres-Criado, D. F. García-Molina, F. J. Mesas-Carrascosa, P. Triviño-Tarradas, Graphic representation of the degree of historical-archaeological evidence: the 3D reconstruction of the “Baker’s House”, *Herit Sci* 10, 33 (2022), pp. 1-14.  
DOI: [10.1186/s40494-022-00670-0](https://doi.org/10.1186/s40494-022-00670-0)
- [6] S. Hermon, J. Nikodem, C. Perlingieri, Deconstructing the VR - data transparency, quantified uncertainty and reliability of 3D models, in: *Proceedings of the 7th International Conference on Virtual Reality, Archaeology and Intelligent Cultural Heritage. VAST’06*. Eurographics Association, Aire-la-Ville, Switzerland, 2006, pp. 123-129.  
DOI: [10.2312/VAST/VAST06/123-129](https://doi.org/10.2312/VAST/VAST06/123-129)
- [7] E. Demetrescu, Extended Matrix Project; Zenodo: Geneva, Switzerland, 2022.  
DOI: [10.5281/zenodo.5957132](https://doi.org/10.5281/zenodo.5957132)
- [8] Extended Matrix project website. Online [Accessed 20 February 2024]  
<https://www.extendedmatrix.org/>
- [9] E. Demetrescu, B. Fanini, E. Cocca, An online dissemination workflow for the scientific process in CH through semantic 3D: EMtools and EMviq open source tools. *Heritage* 6 (2023), pp. 1264-1276.  
DOI: [10.3390/heritage6020069](https://doi.org/10.3390/heritage6020069)
- [10] E. Demetrescu, EM-Blender-Tools: V.1.4.0.dev8; Zenodo: Geneva, Switzerland, 2022.  
DOI: <https://doi.org/10.5281/zenodo.4459272>
- [11] B. Fanini, D. Ferdani, E. Demetrescu, S. Berto, E. d’Annibale, ATON: an open-source framework for creating immersive, collaborative and liquid web-apps for cultural heritage. *Appl. Sci.* 11 (2021), 11062.  
DOI: [10.3390/app112211062](https://doi.org/10.3390/app112211062)
- [12] J. Bonetto, Difendere Aquileia, città di frontiera, *Antichità Altoadriatiche* 49 (2004), pp. 151-196. [In Italian]
- [13] J. Bonetto, Le mura, in: *Moenibus et portu celeberrima. Aquileia: storia di una città*. F. Ghedini, M. Bueno, M. Novello (editors), Ist. Poligrafico dello Stato, Rome 2009, ISBN 9788824013277 pp. 83-92. [In Italian]
- [14] L. Bertacchi, Aquileia: teatro, anfiteatro, circo, *Antichità Altoadriatiche* 41 (1987), pp. 163-181. [In Italian]
- [15] G. Brusin, Gli scavi archeologici di Aquileia nell’anno 1954, *Aquileia Nostra* XXVIII (1957), pp. 5-18. [In Italian]
- [16] P. Basso, D. Dobрева, Aquileia: first results from the market excavation and the Late Antiquity Town walls (part one), Folder 482 (2020), pp. 1-20.
- [17] P. Basso, D. Dobрева, Aquileia: first results from the market excavation and the Late Antiquity Town walls (part two), Folder 483 (2020), pp. 1-32.
- [18] P. Basso, D. Dobрева, S. Laserra, Aquileia: le mura tardoantiche nel settore meridionale della città fra indagini d’archivio e dati di scavo, *Atlante tematico di Topografia antica* XXXII (2022), pp. 87-112. [In Italian]
- [19] C. Tiussi, L. Villa, Aquileia in età tetrarchica e costantiniana. Trasformazioni urbanistiche e monumentali nel settore occidentale, *Aquileia Nostra* 26 (2017), pp. 91-147. [In Italian]
- [20] S. Groh, Ricerche sull’urbanistica e le fortificazioni tardoantiche e bizantine di Aquileia. Relazioni sulle prospezioni geofisiche condotte nel 2011, *Aquileia Nostra* 82 (2011), pp. 153-204. [In Italian]
- [21] P. Blockey, L’area dalla riorganizzazione Massiminaea (Fase IV 286-305 d.C.) ai giorni nostri, in: *L’area archeologica del Monastero Maggiore di Milano*. P. Blockey, N. Cecchini, C. Pagani (editors), Civico Museo Archeologico, Milan 2012, ISBN: 9788897568087, pp. 67-78. [In Italian]
- [22] D. Esposito, M. Fabbri, F. Giovanetti, M. Medri, E. Pallottino, P. Porretta, R.S. Valenzani, R. Volpe, M. Zampilli (editors), *Le mura Aureliane nella storia di Roma. 1. Da Aureliano a Onorio*, Rome TrE-Press, Rome 2017, ISBN: 978-88-948853-92. [In Italian]  
DOI: [10.13134/978-88-948853-92](https://doi.org/10.13134/978-88-948853-92)
- [23] A. Ravotto, *La muralla de Barcino*, Ph.D thesis, Barcelona 2017.
- [24] G. C. Beolchini, L. Milano, E. Antonacci, *Repertorio dei meccanismi di danno, delle tecniche di intervento e dei relativi costi negli edifici in muratura – Definizioni di modelli per l’analisi strutturale degli edifici in muratura, vol. II – Part 1, Tipografie grafiche Scarponi s.r.l., L’Aquila* 2005. [In Italian]
- [25] D. Baatz, Town walls and defensive weapons, in: *Roman Urban Defences in the West*. J. Maloney, B. Hobley (editors), Henry Ling Ltd, London 1982, ISBN 0 906780 23 3, pp. 136-140.  
DOI: [10.5284/1081682](https://doi.org/10.5284/1081682)